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Rayon Reports

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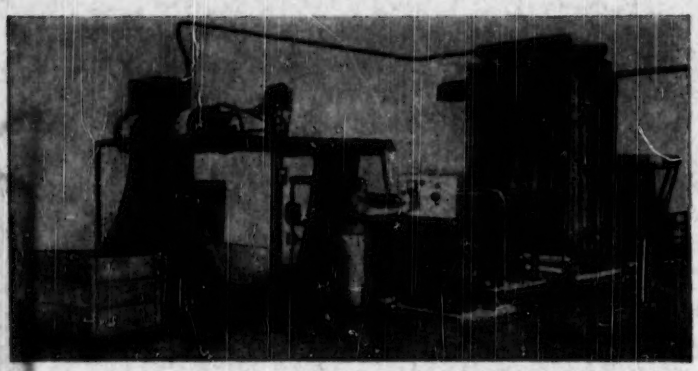
Revolutionary New Vat-Dyeing Process Advances Rayon Washability



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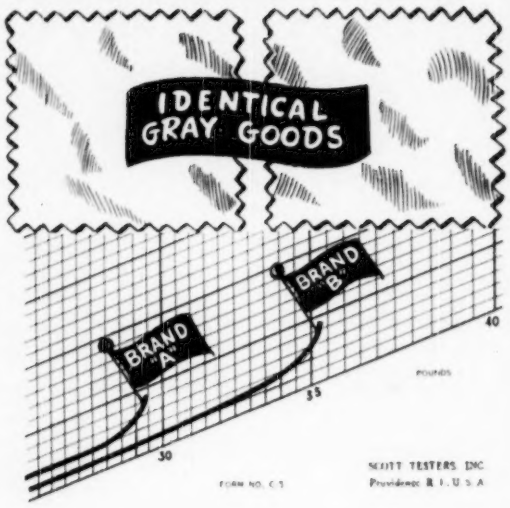

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TEXTILE RESEARCH JOURNAL

VOL. XX, NO. 1 January, 1950

Mechanics of Elastic Performance of Textile Materials

III. Some Aspects of Stress Analysis of Textile Structures—Continuous-Filament Yarns*

Milton M. Platt

Fabric Research Laboratories, Inc., Boston, Mass.

Abstract

Stress-analysis methods for textile materials are illustrated through a study of the forces produced when a continuous-filament yarn is stressed in tension. It is shown that the effects of yarn twist and yarn size on the tensile properties of singles continuous-filament yarns depend upon the stress distribution. Mathematical formulas are derived to express variations in tensile characteristics, both for one-time loading to rupture and repeated stress, as a function of yarn geometry. The influence of fiber inherent properties is described and illustrated by experimental data obtained for viscose rayon, acetate rayon, and nylon of various singles geometry.

Introduction

Stress analysis is that branch of physics which is concerned with the quantitative determination of internal stresses and strains produced in a body as the result of external loads and deformations. Methods of stress analysis have found wide application in the fields of structural and mechanical engineering, where quantitative evaluation of internal forces and movements is an absolute requirement for useful, economical, and safe design. Used in conjunction with sound design principles, stress analysis has made possible the complete blueprinting of engineering structures where particular end-use properties of these structures are desired and can be formulated.

There are tremendous possibilities inherent in the use of stress analysis for the design of textile structures. Its application to mechanical fabrics, cords, ropes, etc., where load-carrying capacity and/or stability of size are important, is obvious. Just as important, however, would be its application to the many other types of textile structures. Such end-use requirements as crush-resistance of apparel fabrics, the combined performance of

* This paper was delivered at the Fall Meeting of the Fiber Society, September, 1947, Princeton, N. J.

Parts I and II in this series appeared in the February and December, 1948, issues of TEXTILE RESEARCH JOURNAL.

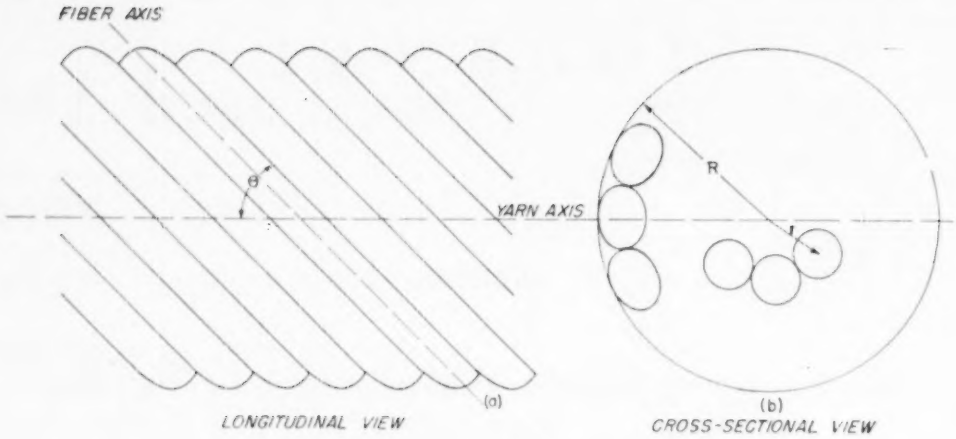


FIG. 1. *Idealized singles yarn geometry.*

coated or laminated fabrics, etc., all depend to a degree upon the inherent properties of the basic fibers and materials comprising the structure. However, the geometric form of these fibers and the type of construction used determine the manner in which these fibers react to the external forces applied in the course of use of the material, and hence influence the utility of the structure to a marked degree.

The need for studying the influence of geometry on the manner in which stresses are distributed in textile structures has been emphasized by various workers in the field. The influence of geometry has been termed "form factor effects." Work of both an empirical and a theoretical nature has already been done along these lines, most of which is related to describing the fundamental geometry of certain textile structures. These workers include Backer, Hamburger, Hertel, Hotte, Peirce, Womersley, and others. However, complete theoretical analysis has been limited chiefly by two properties of textile structures, one inherent and the other arising as a result of geometry, namely:

1. Every textile fiber possesses a nonlinear stress-strain curve for the ordinary rates of loading or straining. Hence, any textile structure in general will exhibit non-Hookean characteristics, making it impossible to describe textile performance by the direct use of well-known engineering formulas. This does not eliminate the possibility of using engineering concepts as a fundamental guide in solving textile problems. Instead, it indicates that the complete solution of a textile problem involving stresses depends upon a quantitative knowledge of the fundamental stress-strain properties of the fiber.

2. Every textile structure, beginning with the yarn, represents a statically indeterminate body [1], which means that stress distribution cannot be established from merely a consideration of the laws of static equilibrium, but that, in addition, the deformation of the structure must be considered. An illustration of static indeterminacy is furnished by comparing the determination of the end supporting forces of a two-span beam *vs.* a single-span beam. These forces can always be found for a single-span beam by using the "law of moments" taken about either end support. An analysis will show such a procedure to be insufficient for the two-span beam. This latter case can be solved only by considering the deformations in the beam.

The Office of The Quartermaster General has been sponsoring a long-term research program aimed toward the understanding of the influence of form factors on the translation of inherent physical properties of fibers into textile structures, and the establishment in quantitative formulas of the relationships between inherent properties and structural properties. The work herein reported is part of this program. Logical sequences of constructions of fiber length, including continuous filament;

yarn twist; yarn size; fabric weave; and ends and picks per in., have been selected for experimental evaluation and theoretical interpretation and generalization.

This paper serves to present the influence of fiber type, yarn size, and yarn twist on the translation of inherent fiber properties into continuous-filament singles yarns. Additional papers will be forthcoming on the effects of fiber length and twist on staple-yarn properties and, later, on the effects of weave and fabric geometry.

Geometry of Singles Continuous-Filament Yarns

The first step in the stress analysis of any structure consists in defining the geometry of the body, usually by assuming an ideal physical form. Theoretical analysis demands the assumption of no variability in form, and a compromise between duplicating actual average shape and the adoption of a geometry which is easy to visualize and handle mathematically. The final check for the rationality of any assumptions is determined partially by judgment, and more convincingly by the agreement between the results arrived at using the assumptions and any experimental results.

The following initial assumptions will be made:

1. The yarn is uniform along its length, and its cross-sectional outline is circular.

2. All fibers within a yarn possess the same properties and are circular in cross section.

3. The center line of each fiber lies in a perfect helix, with the center of the helix located at the center of the yarn cross section.

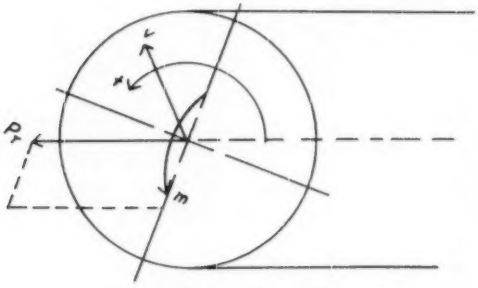


FIG. 2. *General stresses in fibers* (v, t, *and* m *assumed* = 0).

4. The fibers fall into a rotationally symmetric array in cross-sectional view.

5. The diameter of the yarn is large compared with the fiber diameter.

These assumptions result in a yarn geometry illustrated by Figure 1. The helix angle, θ, shown in (*a*) represents the angle between yarn and fiber axes of the outside fibers only. Assumption 4 describes this angle as equal for all fibers which fall into the outer sheath of the yarn. Any other layer of fibers, such as those shown in (*b*) to lie at a distance r from the yarn axis, possesses a helix angle designated by θ_r.

A general equation relating helix angle, turns per in., and diameter can be found in the literature [6] and will not be derived here. The relationship follows:

$$\tan \theta = N\pi KD, \qquad (1)$$

where θ = helix angle; N = yarn twist (turns per in.); $D = 2r$ = bounding diameter of layer of fibers (in.); K = geometrical constant = $\dfrac{D-d}{D}$; and d = fiber diameter (in.).

Equation (1) indicates that for a given yarn twist N, which is constant for all the fibers, the tangent of the helix angles of any layer of fibers is linearly proportional to the distance of the group from the yarn center, just so long as K is constant. By assumption 5, the ratio d/D is considered to be small relative to unity and hence, except for those fibers positioned close to the yarn axis, K will be approximately 1. In addition, for those fibers close to the yarn axis, the helix angle approaches 0, and hence, as will be seen later, variations in K will not influence the stress distribution to any significant degree.

Forces in Fibers

A. Component Effect

The application of an external tensile load, P, along the axis of a yarn results in forces being applied to the various fibers. In general, the only stresses which can possibly act on the cross section of a fiber are: (1) a tensile force, p_r, direction along the fiber axis and normal to the fiber cross section; (2) a shear force, v, acting tangential to the fiber cross section; (3) a bending moment, m; (4) a torsional moment, t. These stresses are illustrated in Figure 2.

It is now assumed that the fibers are perfectly flexible members, incapable of resisting any axial compressive forces. Because of the extremely low modulus of elasticity of textile fibers, in addition to the extremely large ratio of fiber length to fiber diameter, this is a reasonable assumption. As a result of this assumption, the stresses m, v, and t vanish, and the only fiber force acting is a direct tension, p_r. The concept of perfect flexibility is not an uncommon one in engineering. The classical design of the long cables of a suspension bridge depends upon the assumption that only tensile forces are acting, as is the case for many other structures.

Since p_r, which parallels the fiber axis, represents the only force acting upon a fiber, then it is apparent that the contribution of p_r toward the total load P acting on the yarn in tension is:

$$P \text{ per fiber} = p_r \cos \theta_r. \tag{2}$$

Therefore

$$P = \sum p_r \cos \theta_r. \tag{3}$$

Equation (3) states that if the axial tension carried by each fiber is multiplied by the cosine of the helix angle of that fiber, and all such products are summed, the total will represent the axial tensile load acting on the yarn. The completion of such a summation demands knowledge of p_r for each fiber layer, within which θ_r is constant. Such a method would be tedious and require a new solution for each yarn size considered, and hence a simpler mathematical form of equation (3) has been derived.

It is now assumed that the individual fibers in the yarn are considered to be consolidated into an equivalent solid continuous medium rather than a group of discretely individual fibers. However, it is still considered that at a distance r from the yarn center, the force, p_r, remains inclined to the yarn axis at the angle θ_r which the fiber at that position possessed previously. In addition, the total transformed yarn denier is assumed to be unchanged. The cross-sectional area of this new yarn will be discussed later.

As a result of this transformation it is now possible to treat the yarn as a continuous rather than a discontinuous medium, with the use of differential elements of area as opposed to individual fibers. Figure 3 illustrates the element of force, dp_r, acting on the element of area defined by the shaded annular ring.

The magnitude of the force dp_r is equal to the product of the stress intensity (force per unit area), f_r, and the element of area, dA, normal to the force. Reference to Figure 3 will show that this may be written as:

$$dp_r = f_r dA = f_r(2\pi r)dr'. \tag{4}$$

However, it is apparent that:

$$dr' = dr \cos \theta_r.$$

Therefore:

$$dp_r = f_r 2\pi r \cos \theta_r dr. \tag{5}$$

The component of the force, dp_r, parallel to the yarn axis, dP_r, may be written:

$$dP_r = dp_r \cos \theta_r = f_r 2\pi r \cos^2 \theta_r dr. \tag{6}$$

The sum of all forces, dP_r, represents the total axial yarn load and is found from:

$$P = \int_{r=0}^{r} dP_r = 2\pi \int_{r=0}^{r} f_r r \cos^2 \theta_r dr. \tag{7}$$

In order to integrate equation (7) it is necessary to express both f_r and θ_r as functions of r. From equation (1):

$$\tan \theta = N\pi KD,$$

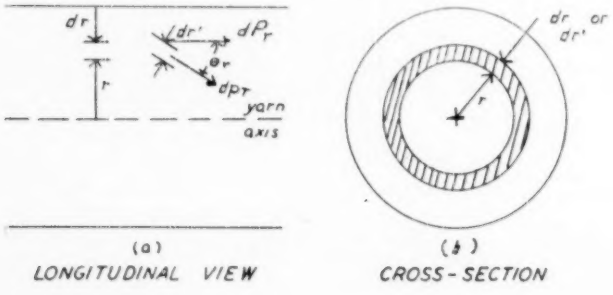


FIG. 3. *Elements of forces in solid yarn.*

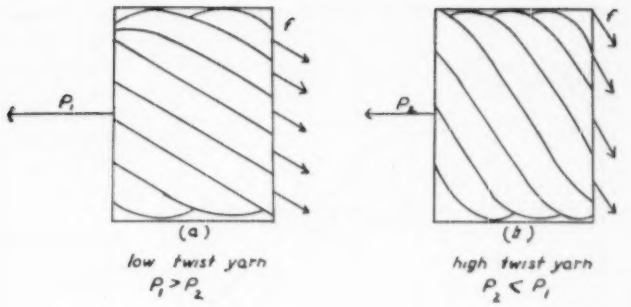


FIG. 4. *Effect of helix angle on utilization of filament strength (component effect).*

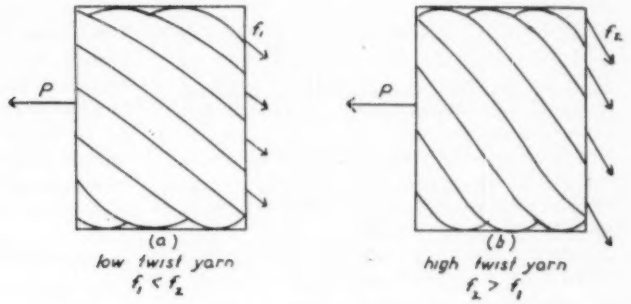


FIG. 5. *Effect of helix angle on filament forces (component effect).*

which becomes for the assumed solid yarn:

$$\tan \theta_r = N\pi \frac{(2r - dr)}{2r} 2r;$$

$$\tan \theta_r = 2\pi Nr. \tag{8}$$

From the identity:

$$\cos^2 \theta = \frac{1}{1 + \tan^2 \theta}$$

it is apparent that:

$$\cos^2 \theta_r = \frac{1}{1 + 4\pi^2 N^2 r^2}. \tag{9}$$

Substituting equation (9) into equation (7):

$$P = 2\pi \int_{r=0}^{r} f_r \frac{r dr}{(1 + 4\pi^2 N^2 r^2)}. \tag{10}$$

The evaluation of the dependency of f_r upon r will be described later. Equation (10) was derived without any consideration of the inherent properties of the fibers comprising the yarn. It is dependent only upon yarn geometry and hence applies to continuous-filament yarns made of any fibers which satisfy the assumptions previously given. Since the equation was derived from laws of static composition of forces, the effect is termed the "component effect." The component effect results in the important fact that the higher the helix angle the greater the fiber tensile stresses when a given axial load acts on a continuous-filament yarn, since, from equation (10), the value of f_r increases when N increases and P is held constant. Conversely, with equal fiber stresses, the most highly twisted yarn will have the lowest axial yarn load, since P decreases as f_r is held constant and N increases. These effects are illustrated in Figures 4 and 5.

B. Serigraph Effect

Equation (10) requires for its solution expressing f_r, the tensile stress intensity, as a function of r, the distance from the yarn center. A first approximation would be to assume f constant with r (*i.e.*, equal stress intensity at all points in the yarn cross section). However, conditions of continuity of distortion must be satisfied, and, as stated previously, the solution of statically indeterminate structures requires a study of the deformations involved. The "serigraph effect" quantitatively establishes the effect of distortions upon the stress distribution. Whereas the component effect is general, dependent only upon yarn geometry, the serigraph effect, while

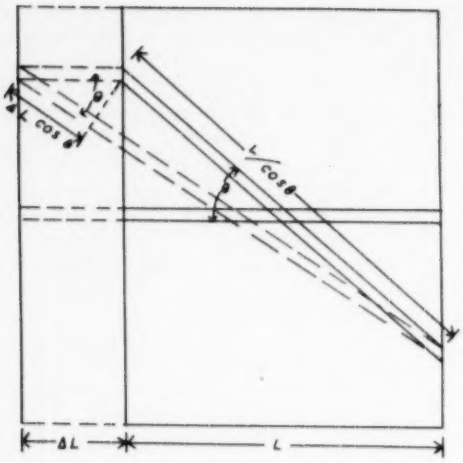


FIG. 6. *Deformations in twisted yarns.*

caused by yarn geometry, depends for its magnitude upon inherent fiber properties.

Because of the helix angle, the actual length of inclined fibers in a given length of yarn exceeds the yarn axial length, the excess being functionally related to the cosine of the helix angle. Figure 6 is a sketch of a yarn with two filaments, one inclined at an angle θ to the yarn axis and the other parallel to the yarn axis. The yarn is shown with an extension ΔL, or an equivalent axial strain $\frac{\Delta L}{L}$. This yarn axial strain, $\frac{\Delta L}{L}$, also represents the unit strain of the center fiber which has a helix angle of 0. The inclined fiber possesses a length $\frac{L}{\cos\theta}$. From Figure 6 it is apparent that the absolute elongation of the inclined fiber can be very closely approximated as:

$$\Delta L_\theta = \Delta L \cos\theta.$$

Therefore, the unit strain, ϵ_θ, in any fiber inclined at an angle θ to the yarn axis may be determined from:

$$\epsilon_\theta = \frac{\Delta L \cos\theta}{L/\cos\theta} = \frac{\Delta L}{L}\cos^2\theta; \qquad (11)$$

or

$$\epsilon(\text{fiber}) = \epsilon(\text{yarn})\cos^2\theta. \qquad (12)$$

Since $\cos^2\theta$ is equal to or less than unity, it is clear that for all helix angles greater than zero the fiber strain is less than the yarn strain. In addition, as shown by equation (9), the farther the fiber from the yarn axis the greater the value of θ, and, therefore, the smaller the value of $\cos^2\theta$. Hence, the farther the fiber from the yarn axis the smaller the fiber strain. Substituting equation (9) into (12):

$$\epsilon_\theta = \frac{\epsilon_0}{1 + 4\pi^2N^2r^2}^{*} \qquad (13)$$

(ϵ_θ = strain in fiber inclined at angle θ to yarn axis; ϵ_0 = yarn strain or strain in uninclined fibers.)

For any textile fiber, strain is functionally related to stress for given testing conditions such as rate of loading or straining. The magnitude of the stress being borne by a fiber when it is strained a given amount may be found from the stress-strain diagram for that particular fiber. Usually it is found that as the strain decreases the stress also decreases, an exception being the dip in a stress-strain curve beyond the yield point when tests are made slowly at a constant rate of elongation. It has just been shown that the strains present in a loaded yarn vary with the distance of the filament from the yarn axis. The center filaments ($\theta = 0°$) are always subjected to greater strains than are any of the

* A more precise expression, based on assuming Poisson's ratio = ½, is

$$\epsilon_\theta = \sqrt{\frac{(1+\epsilon_0)^2 + 4\pi^2N^2r^2}{(1+\epsilon_0)(1+4\pi^2N^2r^2)}} - 1.$$

(The above equation should be used if very high helix angles or fiber elongations are encountered.)

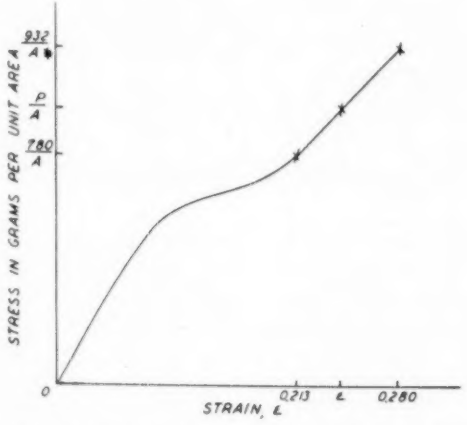


FIG. 7. *Stress-strain diagram (constant rate of load) for 600/208/0.3 acetate yarn. *A = Cross sectional area of 600-denier yarn.*

other filaments. Hence, the center filaments can be stressed to rupture while the remaining filaments are stressed below their rupture loads. As soon as the center filaments fail, there occurs a rapid progressive rupturing of all remaining filaments and the yarn breaks. As a result, the full breaking strength of the sum of the filaments theoretically can never be attained. Instead, the maximum strength of the yarn is limited by the sum of the components of the fiber forces when the center fibers have reached their ultimate elongation. When this yarn elongation is reached, only a portion of the strength of the inclined fibers contributes to yarn strength. The precise amount of this contribution depends upon the stress-strain curve of the material, in addition to the magnitude of the helix angle, and will now be evaluated for 600/208 acetate yarn.

The stress-strain diagram of 600/208/0.3 acetate yarn is shown in Figure 7. The curve was obtained from a constant-rate-of-load IP-2 machine. Since the yarn twist is so slight, it is assumed that the fiber inclination is negligible.

Now, at yarn rupture the stress intensity carried by the fibers is equal to $\frac{932}{A}$ g. per unit area (where A is the cross-sectional area of the yarn) at a strain of 0.280. Fibers inclined to the yarn axis are subjected to a strain of:

$$\epsilon_\theta = \frac{0.280}{1 + 4\pi^2 N^2 r^2} \tag{14}$$

and are carrying a stress of P/A g. per unit area. From Figure 7 it is seen that the shape of the stress-strain curve close to rupture is essentially linear. The equation for this portion of the stress-strain curve may be written as:

$$\frac{P/A - 780/A}{\epsilon - 0.213} = \frac{932/A - 780/A}{0.280 - 0.213} = \frac{2240}{A}.$$

Thus:

$$\frac{P}{A} = f = \frac{2240\epsilon + 304}{A}. \tag{15}$$

Substituting equation (14) into equation (15):

$$f = \frac{\dfrac{628}{1 + 4\pi^2 N^2 r^2} + 304}{A}. \tag{16}$$

Equation (16) defines the stress distribution, f, at yarn rupture as a function of yarn twist, N, and distance of the fiber from the yarn center, r. It is apparent from this equation that, for a given yarn twist, the further the fiber from the yarn center the smaller the stress carried by that fiber at yarn rupture. In addition, for a given yarn size, the greater the yarn twist the less the fiber stress at a given distance from the yarn center. Figure 8 illustrates the variations of stresses within singles yarns in accordance with equation (16).

The determination of the variance of stress with position as determined by equation (16) now permits the integration of equation (10) for the 600/208 acetate yarn. Following substitution of (16) into (10), the following expression results after expanding logarithmic and fractional terms into a power series and neglecting terms possessing powers of R greater than 4:

$$P = 4(233 - 7450N^2R^2), \tag{17}$$

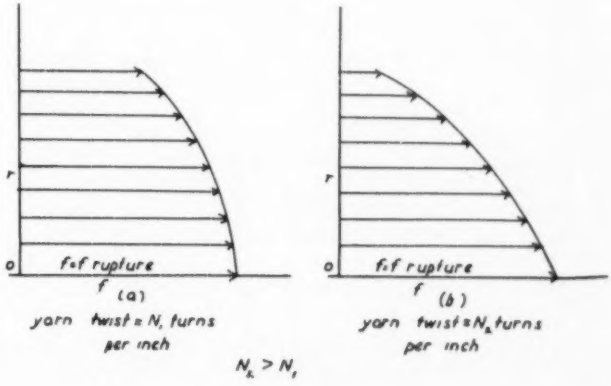
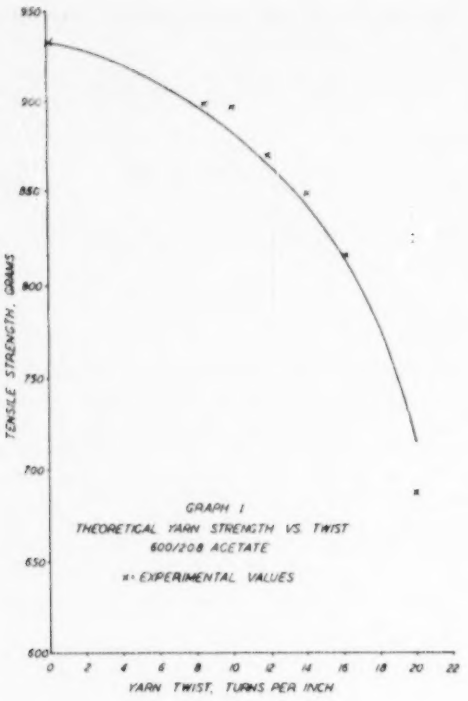
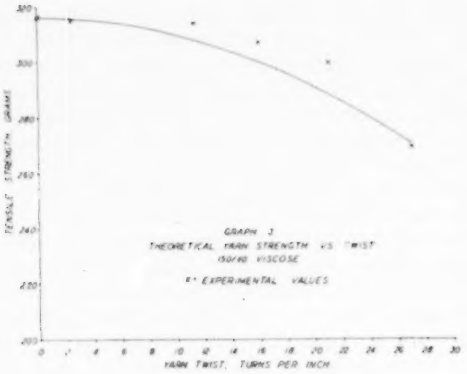


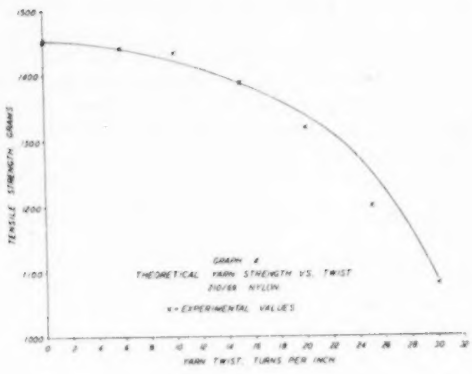
FIG. 8. *Tensile stress distribution in singles yarn.*



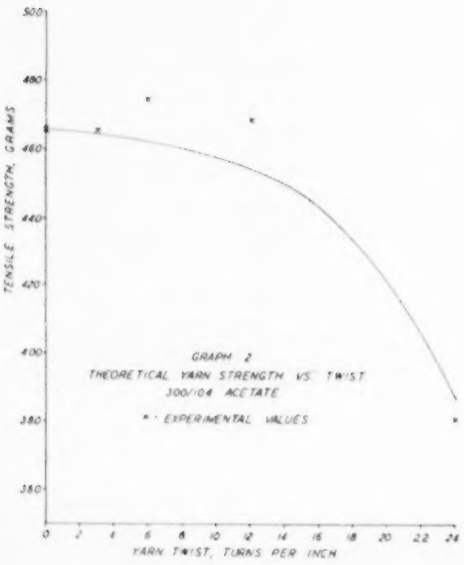
GRAPH 1
THEORETICAL YARN STRENGTH VS. TWIST
600/208 ACETATE
x = EXPERIMENTAL VALUES



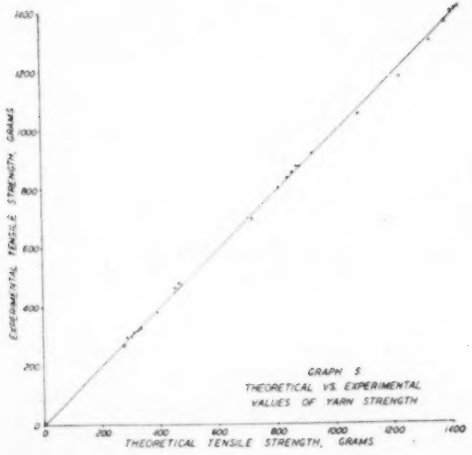
GRAPH 3
THEORETICAL YARN STRENGTH VS. TWIST
150/40 VISCOSE
x = EXPERIMENTAL VALUES



GRAPH 4
THEORETICAL YARN STRENGTH VS. TWIST
210/68 NYLON
x = EXPERIMENTAL VALUES



GRAPH 2
THEORETICAL YARN STRENGTH VS. TWIST
300/104 ACETATE
x = EXPERIMENTAL VALUES



GRAPH 5
THEORETICAL VS. EXPERIMENTAL
VALUES OF YARN STRENGTH

TABLE I. EQUATIONS GIVING EFFECT OF TWIST ON YARN STRENGTH

Yarn	Equation*
150/40 viscose	$P = 316\text{-}11{,}200N^2R^2$
210/69 nylon	$P = 8{,}100\left[\frac{1 + 6\pi^2N^2R^2}{(1 + 4\pi^2N^2R^2)^2}\right] - \frac{6{,}650 \ln (1 + 4\pi^2N^2R^2)}{4\pi^2N^2R^2}$
300/104 acetate	$P = 466\text{-}14{,}900N^2R^2$
600/208 acetate	$P = 932\text{-}29{,}800N^2R^2$

* Equations for all materials simplified by expansion into power series except that for nylon, the series for which converges very slowly; hence, the actual equation is given for this material.

where P = tensile strength of yarn (g.); N = yarn twist (turns/in.); and R = yarn radius (in.).

Equation (17) defines the breaking strength of the 600/208 acetate yarns in terms of the yarn radius and twist. Similar equations have been derived for the various materials as listed in Table I.

With respect to the use of such equations as those given in Table I, the twist, N, and the radius, R, should represent both these quantities at yarn rupture. When a yarn is being strained to rupture, the twist per unit length is continually decreasing as the elongation increases. If N_s is the yarn turns per inch at no load, then at yarn rupture the twist N is given as:

$$N = \frac{N_s}{1 + \epsilon_r}, \tag{18}$$

where ϵ_r is the unit strain at rupture. The yarn radius will also decrease with strain. Assuming, momentarily, that the yarn is composed of solid fibrous material (complete packing), then for most high polymers which extend at constant volume the square of the yarn radius is inversely proportional to the total length of the sample while it is being stressed. Thus, if R_s^2 is the square of the radius at no load, then the square of the yarn radius at rupture, R^2, is:

$$R^2 = \frac{R_s^2}{1 + \epsilon_r}. \tag{19}$$

The original yarn radius, R_s, can be calculated. It is easily shown that for a solid yarn the value R_s^2 in square inches is related to the yarn denier and the fiber specific gravity as follows:

$$R_s^2 = 0.055 \times 10^{-6} \times \frac{\text{yarn denier}}{\text{fiber specific gravity}}. \tag{20}$$

If the yarn denier and fiber specific gravity are known, then equation (20) would give the value of R_s^2 for a solid yarn. The bulk factor of the yarn, however, must be considered before a realistic value of the radius can be calculated. This is best taken care of by use of a bulk specific gravity for the yarn. Peirce [4] has reported that for firm cotton and viscose yarns a bulk specific gravity of 0.9 gives reasonably accurate results, and, although determined for staple yarns, should apply closely to continuous-filament yarns. Others have indicated acetate yarns to have a bulk specific gravity of about 0.86. While no data are available for nylon, the value of 0.9 has been used in the strength calculations.

Utilizing the equations given in Table I for a pedigreed set of yarns, the strength-twist curves shown as Graphs 1, 2, 3, and 4 were determined. Experimental values of strength are also shown on the graphs. It is to be noted that reasonably good agreement has been obtained between the theoretical and the experimental strengths. The experimental data for all the materials follow in general the same type of parabolic strength-twist curve as the calculated curves do, except for the 300/104 acetate. This yarn is the only one of the group which was spun directly to different twists at the plant. The other yarns were all spun from the same lot of original low-twist yarn. Hence, the relatively poor agreement for the data shown in Graph 2 may be the result of variation in fiber properties. However, when all of the calculated and actual strengths are plotted against each other, a linear agreement line having a slope close to 45° results, as shown in Graph 5.

Influence of Fiber Properties

It has been indicated that the shape of the stress-strain curve is important in determining the magnitude of the serigraph effect. Each of the equations given in Table I, except that for nylon, can be written in the form:

$$P = a - bN^2R^2, \tag{21}$$

where a represents the zero twist strength, and N and R are the yarn twist and yarn radius at rupture, respectively. The quantity b determines the extent to which a given geometry affects yarn strength. Actually, the ratio b/a determines this extent. It can be shown that this ratio is functional with the stiffness of the fiber at high loads, as evidenced by the shape of the stress-strain diagram. Consider the hypothetical stress-strain diagrams of two fibers,

A and B, as shown in Figure 9. Let it be assumed that both fibers A and B possess precisely the same properties, both geometric and inherent, except that the shapes of their stress-strain diagrams are different. Then, if yarns of similar geometry are made from each of these fibers, it is clear that the component effects would be alike. However, with respect to the serigraph effect, it is clear from Figure 9 that although at yarn rupture the center fibers in both yarns would be supporting equal stresses, f_r, the inclined fibers in yarn A would be supporting stresses $(f_\theta)_A$ while the inclined fibers in yarn B are subjected to stresses as low as $(f_\theta)_B$. From Figure 9 it can be seen that the strength of yarn A will exceed the strength of yarn B.

In this connection, it is interesting to consider the work of Peirce [5] in discussing the loss in strength of cotton yarns after the optimum twist is exceeded. The general equation for strength fall-off is given by Peirce as the factor:

$$\frac{1}{1 + 0.0126\eta K^2},$$

where η is a constant depending on zone-of-rupture diameter and yarn diameter, and K is the yarn twist multiplier, proportional to NR. This factor may be approximated as:

$$1 - a(0.0126\eta N^2 R^2),$$

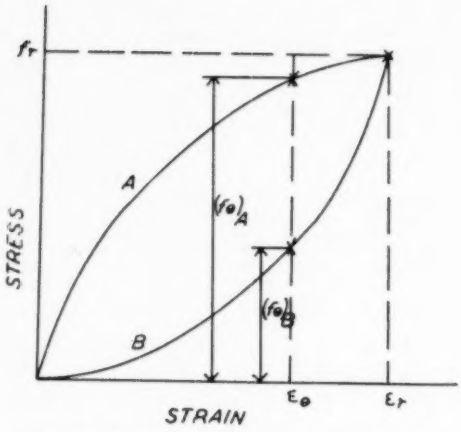


FIG. 9. *Hypothetical stress-strain diagrams of two materials.*

where a is the constant of proportionality relating twist multiplier to the product of yarn twist and yarn radius. This last formula expresses the influence of only the component effect. Actual experimental results check the above formula if the value of 0.0126 is replaced by 0.0140, which, according to Peirce, "is of the right order of magnitude but greater than would be expected of the purely geometric effect in a regular yarn."

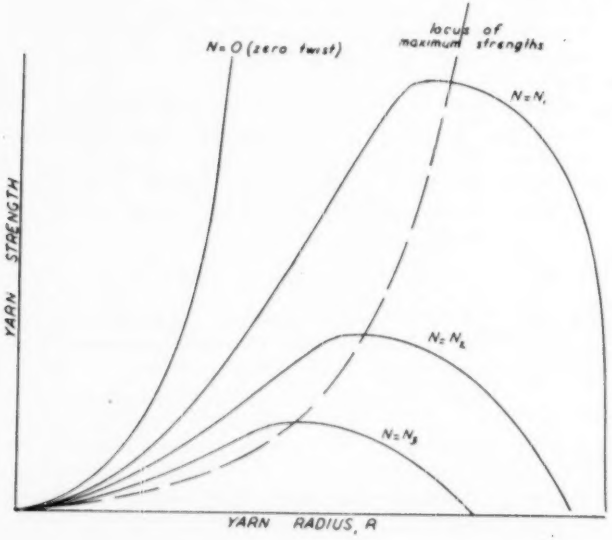


FIG. 10. *Effect of yarn size* (R) *on yarn strength at various twists,* N ($N_0 < N_1 < N_2 < N_3$). *Locus of maximum strengths is such that* N×R *is constant.*

It is clear, however, from what has been discussed already, that the value of 0.0140 could be significantly associated with the serigraph effect, since this factor has the ultimate result of producing a lower strength than would be expected from only the component effect. The elastic properties of the fiber can influence the effect of yarn geometry.

It is interesting to consider the effect of increasing the yarn size while keeping the yarn twist (turns per in.) constant. Equation (21) can be written in more general terms to take into consideration differences in initial yarn radius:

$$P = R^2(a' - b'N^2R^2). \qquad (22)$$

The maximum value of P produced by varying R can be calculated from equation (22) by:

$$\frac{\partial P}{\partial R} = 0$$

or

$$\frac{\partial P}{\partial R} = 2a'R - 4b'N^2R^3 = 0.$$

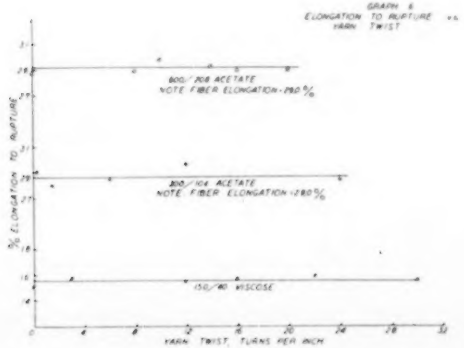
Therefore, $R = 0$ (zero strength), or

$$N^2R^2 = \frac{a'}{2b'};$$

$$NR = \sqrt{\frac{a'}{2b'}}. \qquad (23)$$

Equation (23) indicates that for a given fiber (a' and b' are material constants), yarn strength at a given twist can be increased by increasing yarn weight up to the point where the product of yarn twist and yarn radius satisfies equation (23). Further increases in yarn weight will result in a decreased strength. Moreover, independent of what yarn twist is considered, the product of this yarn twist, N, and yarn radius, R, will be the same at the maximum strength point. The value $(N \times R)$ can be shown to be proportional to the "twist multiplier" as used in staple-yarn terminology)* since the yarn radius varies inversely as the square root of the yarn count (cotton system).

The effect of yarn size on yarn strength at different twists is indicated graphically in Figure 10.



Yarn Stress-Strain Characteristics

A. Elongation to Rupture

In the discussion relating to the magnitude of the serigraph effect it was shown that at yarn rupture the strains present among the various fibers in a yarn varied with the helix angle. Yarn rupture occurred at the point where the shortest fibers—*i.e.*, those fibers which lie close to the yarn axis and hence possess zero helix angle—reach their limiting extension. This limiting extension is also the extension of the yarn to rupture. The effect of yarn twist or yarn size is merely to alter the distribution of extensions among the various fibers.

Since the fibers close to the yarn axis are the first to fail as a result of tension, it can be concluded that the yarn elongation to rupture should be constant, independent of the yarn twist or yarn size. It is true that exceedingly high yarn twists can produce initial spinning tensions in the fibers which are of sufficient magnitude to alter their elastic properties by, say, cold-working the fiber. Such a yarn would not be expected to exhibit the same elongation to rupture as a low-twist yarn. However, where spinning does not influence the elastic properties of the fiber, the yarn elongation should not be altered by changing either the yarn twist or the yarn size.

Graph 6 plots the elongation to rupture of a series of singles yarns with various twists and yarn weights. It can be seen from this graph that changing the twist has not produced any substantial changes in the elongation to rupture. In addition, for the two acetate yarns, the yarn elongation is substantially the same as the fiber elongation.

B. Stress-Strain Curves

It has been shown that twist produces the following effects on the properties of continuous-filament singles yarns:

* Twist multiplier $= \frac{N}{\sqrt{C}}$, where C, the cotton count, varies inversely as the yarn denier.

1. The higher the twist the lower the yarn strength.

2. Yarn elongation is independent of yarn twist just so long as spinning does not alter the mechanical properties of the fibers.

Figure 11 shows the theoretical relationship that might be expected between the stress-strain diagrams of a group of yarns with successively higher twists. These curves have been drawn so as to satisfy conditions 1 and 2 above. In addition, however, they have been drawn so that at any load below rupture the elongation of the higher-twist yarns exceeds that of the lower-twist yarns. This must be so, since for the same total load on the yarns the fibers in the high-twist yarns are subjected to a higher axial tension than are those in a lower-twist yarn. Both the component and serigraph effects produce this difference in fiber loads. Since higher fiber tensions produce greater fiber extensions, the trends shown in Figure 11 are logical.

The change in shape as well as the change in end points of such curves, as shown in Figure 11, is capable of mathematical analysis and prediction. The procedure is a laborious one involving first the determination of the empirical formula of the fiber (or zero-twist yarns) stress-strain curve. The component and serigraph effects are then written analytically for the whole range of loads from zero to rupture, in terms of yarn twist, N, and yarn size, R. The final expression would be the stress-strain equation for a given material in terms of both N and R.

However, it is possible to deduce the general results of such an involved calculation by reference to Figure 11:

1. The higher the yarn twist the lower either the secant modulus or the tangent modulus of the stress-strain curve.

2. The higher the yarn twist the lower the energy absorption to rupture. This is so, since the stress-strain curve for a high-twist yarn lies below that of a low-twist yarn and the ultimate elongations are equal.

C. *Elastic Characteristics of Yarns*

The performance of textile structures in end use is very rarely a one-time loading-to-rupture proposition. Instead, most textile products are usually subjected to a continual repeated stress action, the magnitude of the stresses being below that rupture load which the specimen is capable of withstanding *previous* to use. Mechanical failure of a material in end use occurs when, as a result of repeated loading and unloading, the structure is incapable of absorbing and returning the imparted energy without the occurrence of failure as either a permanent deformation or an actual rupture of the component parts, depending upon the end-use requirement. One peculiar physical characteristic of textile materials which heretofore has identified them as unpredictable engineering materials has been the fact that the elastic properties depend upon the previous loading history. Most textiles exhibit the delayed components of deflection, primary and secondary creep, the magnitude of each being a function of load, time, and inherent properties.

More specifically than actual load, the internal stresses govern the magnitude of the delayed deflections for a given material, and since the stress distribution of filamentous singles yarns changes with twist, it is to be expected that the repeated stress properties would also depend upon twist. Three criteria of repeated stress performance have been considered: (1) secondary creep, (2) corrected residual elongation, and (3) elastic performance.

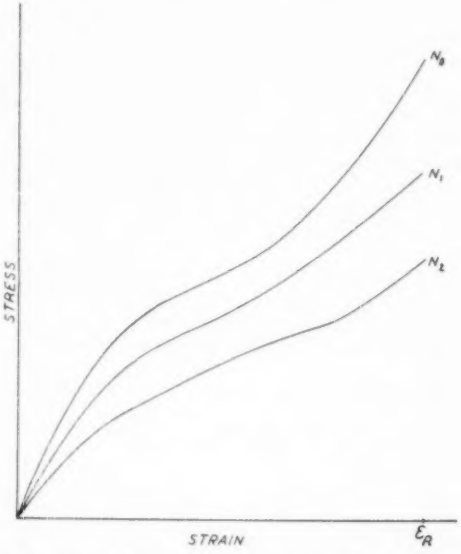
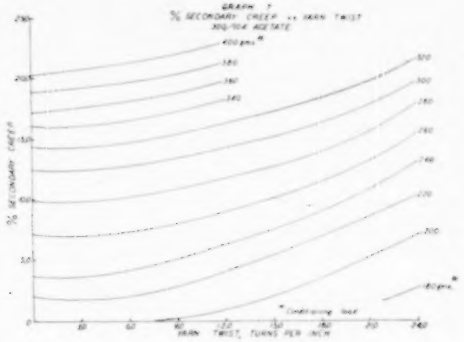
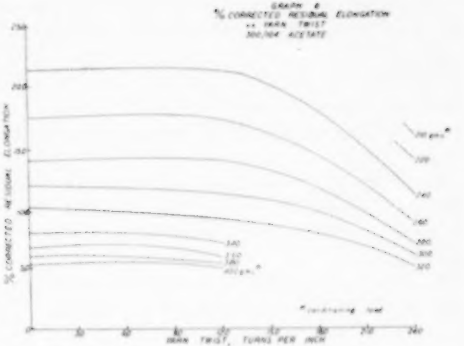


FIG. 11. *Theoretical effect of yarn twist, N, on stress-strain diagrams* ($N_2 > N_1 > N_0$).





The data given in this section on elastic properties have already been reported by Hamburger [2]. The graphs expressing the data are repeated for convenience in following the discussion.

1. *Secondary Creep.*—Secondary creep is that portion of the delayed deflection exhibited by a material which is not recoverable with time following load removal. The removal of secondary creep results in a change in the load-extension diagram, with an attendant loss in energy-absorption capacity. It has been found that poor abrasion-resistance characterizes a material most of the deflection of which is attributable to secondary creep. Both poor crease-resistance and poor dimensional stability also follow when most of the elongation possessed by a material can be ascribed to secondary creep. On the other hand, in order to resist rupture due to stress concentrations, secondary creep can often be a valuable asset to a material. Hence, it can easily be seen that the determination of this property is important to the evaluation of a textile.

The effect of both load and twist on the secondary creep of 300/104 continuous-filament acetate rayon is given in Graph 7, which illustrates two points: (1) the secondary creep is a function of conditioning load, the greater the load acting on the untwisted elements the greater the secondary creep; (2) at a given conditioning load, the greater the twist the greater the secondary creep.

Point (1) states an inherent property of acetate rayon. Other materials may or may not possess a similar characteristic. For example, nylon shows a much smaller change in secondary creep with load than does acetate rayon. However, in the case of the acetate rayon, it becomes apparent why twisting increases the secondary creep at a given conditioning load. For a given yarn load, the internal filament forces are greater for a twisted than for an untwisted yarn. This has been explained as being caused by both the component and serigraph effects. Since secondary creep increases with load on an untwisted yarn, the increase in secondary creep with twist at a given yarn load is explained. For the nylon mentioned above, one should find secondary creep to be less influenced by yarn twist than for acetate rayon. Except for such effects as yarn slippage due to twist removal, this should certainly be the case.

2. Corrected Residual Elongation.—If a material possesses secondary creep, the process of mechanical conditioning generally causes a decrease in the extensibility of the specimen. It is of value to know the extensibility of such a mechanically conditioned material, since a large decrease in the elongation after conditioning reflects a large decrease in the energy-absorption capacity of the material following repeated stressing in use. A material may show a high elongation to rupture on a one-time loading basis, and may be selected for a particular end use whenever such a large elongation is desirable. However, if this elongation is not attainable again, and the end-use requirement is not a one-time use, the choice of this material may not have been the best.

The percent corrected residual elongation delineates the elongation to rupture following the removal of secondary creep. It is termed "residual" since it represents the remaining elongation. The expression "percent corrected" is used, since the elongation is expressed as a percent of the new gage length—*i.e.*, the sum of the original gage length before stressing plus the added gage length due to secondary creep removal.

Dependent as it is upon secondary creep removal, the percent corrected residual elongation should be expected to vary with both load and twist. Graph 8 plots the effects of load and twist on the percent corrected residual elongation.

Two points are worthy of note from examination of this graph:

1. Inherently, acetate rayon shows a decrease in the corrected residual elongation with load. This decrease parallels the increase in secondary creep with load.

2. At a given load, the greater the twist the less the percent corrected residual elongation. The explanation for this effect is similar to that given for the increase in secondary creep with twist at a given load.

It is interesting to note that the shapes of all the curves in Graphs 7 and 8 are essentially parabolic with twist at constant load. This same general shape resulted for the effects of twist on tensile strength. The deviation of the stress distribution from uniformity as twist changes is also parabolic with twist. Hence, the tie-in between stress distribution, as produced by yarn geometry, and repeated-stress performance appears to be justified.

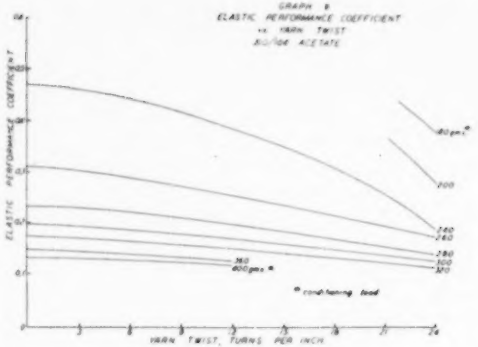
3. Elastic Performance.—The preceding paragraphs have discussed certain of the changes in elastic properties exhibited by textiles following repeated stressing. The extent to which a material duplicates its original stress-strain characteristics, taking into account the effects of both primary and secondary creep, is indicated by the elastic performance coefficient. This coefficient can be applied to all types of loading: tension, bending, torsion, bulk compression, etc., and is determined from the repeated-stress data. The method for calculation has been described by Hamburger [2]. Qualitatively, the coefficient should be regarded as a numerical index which expresses, as a fraction of unity, the degree of perfect spring-like behavior exhibited by a material.

Graph 9 plots values of the elastic performance coefficient as a function of both load and twist. Once again, it is clear that two predominant effects are evidenced:

1. The higher the load the smaller the elastic performance coefficient.

2. At a given load, the greater the twist the poorer the elastic performance.

Also, it should be apparent that condition 2 above depends upon the inherent property indicated by condition 1, since were it not for the fact that higher loads reduce the elastic performance, the effects of higher filament stresses in highly twisted yarns would not produce reductions in the elastic performance coefficient.



Conclusions

The concepts developed in this paper represent only a part of the type of quantitative "applied mechanics" of textile structures, the complete establishment of which is the over-all, long-range objective of the research being done for the Quartermaster Corps. The work has been concerned with the development of rational laws describing the influence of geometrical factors on textile performance, beginning with the smallest textile units with respect to size but the most complex from a technical point of view—namely, the fiber and the yarn. It is felt that the yarn form factors isolated and described in the main body of this paper constitute a necessary part of the logical development of geometrical effects; and, just as fibers and yarns are the fundamental units in the construction of a textile product, so must their mechanical properties be regarded in relation to the mechanical properties of the finished structure. It has been shown that stress analysis permits quantitative explanation and prediction of the following effects:

1. Rupture properties of singles continuous-filament yarns. Both rupture load and rupture elongation are capable of physical analysis and correlation with the properties of the fiber.

2. Energy absorption. The shape of the stress-strain diagram of yarns can be quantitatively predicted from the fiber stress-strain diagram and the influence of yarn geometry upon the energy-absorption properties determined.

3. The dependency of the elastic properties of yarns upon yarn geometry has been described and explained. In particular, it has been shown how stress distribution is responsible for changes in the visco-elastic characteristics exhibited by yarns comprised of known fibers and how these changes may be calculated.

4. Optimum yarn sizes for different-twist yarns have been shown to be capable of quantitative determination. Rational laws governing the relationship between yarn size and twist have been developed.

5. It has been shown that the extent to which yarn geometry influences yarn properties is partly functional with the inherent fiber properties. In particular, it has been shown that the rupture properties can be described in terms of constants of the fiber as determined by its stress-strain diagram. Future work on this program is concerned with the determination and classification of the constants for a wide variety of textile fibers.

In addition to yielding information on the performance of singles continuous-filament yarns, the broad ideas developed have led to the extension of certain of the concepts to other higher-order textile structures, the results of which will be published in later works, but will be briefly mentioned here:

1. Similar performance characteristics of staple-fiber yarns [3]. It has been found that when fiber slippage is properly taken into account, many of the properties of singles staple-fiber yarns are capable of evaluation by the same general methods as those presented herein. The influences of staple-fiber yarn geometry on the translation of strength, elongation, and visco-elastic characteristics are all capable of analytic description.

2. Characteristics of plied continuous-filament yarns. It can be shown that the elastic characteristics of plied yarns, for example, are critically dependent upon the presence or absence of a core which lies in the center of the yarn. For example, for a 7-ply yarn one can show that increase in ply twist, maintaining yarn twist constant as it lies in the ply, causes a parabolic decrease in the energy to rupture. On the other hand, for a 3-ply yarn increases in the ply twist would show a parabolic increase in energy absorption to rupture.

3. Certain of the methods developed in this work are capable of being translated directly into fabric-geometry effects. For example, the effects of high fabric crimp in tightly woven fabrics, both on tensile strength and elongation, are capable of being analyzed in much the same manner as those for the serigraph effect.

From the examples it is clear that the mechanical properties of textile structures are capable of being analyzed and explained, and, hence, predicted. The ability to blueprint and design fabrics for mechanical end uses is possible. It is felt that other end uses which are dependent upon the so-called "obscure" properties of textiles, such as wear-resistance, drape, etc., are also capable of engineering design, once the physical analogy of the tactile property is established.

Acknowledgment

The author wishes to make acknowledgment to the Textile Section, Research and Development Branch, Office of The Quartermaster General, and the Office of Naval Research, which sponsored this work, and expresses his appreciation to Dr. W. J. Hamburger and Mr. E. V. Painter for their assistance and encouragement.

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The Thermodynamics of One-Component and Two-Component Elastic Systems

Sidney M. Katz *

Contribution of The Textile Foundation and Frick Chemical Laboratory, Princeton University, Princeton, New Jersey

Abstract

The thermodynamic analysis of stress in one-component, one-phase elastic systems is reviewed, and it is suggested that the stress be evaluated in terms of entropy and enthalpy contributions. The analysis is then extended to two-component, two-phase systems, and the necessary equations are derived. By so doing, the temperature effect on swelling is taken into account. In addition, the basic hypotheses of the kinetic theory of rubber elasticity are shown to lead to conclusions which are thermodynamically impossible.

Introduction

The thermodynamic equations for elastic materials which were derived by Wiegand and Snyder [18] and later modified by Elliott and Lippmann [2] apply to a single-phase, one-component system and are intended for the study of rubber and rubbery materials. In analogous work on textile fibers the experimental work has been carried out in the presence of water [1, 19], alcohol-water mixtures [11], or aqueous or alcoholic salt solutions [11]. In these two-phase systems of two or more components, the equations of Elliott and Lippmann or of Wiegand and Snyder can serve only as first approximations; for more exact considerations it is necessary, as Woods [19] has already pointed out, to take into account the effect of the swelling agent on the temperature coefficient of stress of the material.

The object of this paper is to develop the equations applicable to a two-phase, two-component system by an extension of the equations for the one-component model.

The simpler one-component system will be considered in some detail first, and the hypotheses underlying the resultant equations will be examined. In this connection, the problems of hysteresis and stress-relaxation will be analyzed, and the definition of the entropy contribution to the tension will be reviewed. It will also be shown that a rigorous thermodynamic analysis suggests a modification of the kinetic theory of rubber elasticity.

In this study, most of the symbols are those commonly used in many thermodynamics texts (see Lewis and Randall [10] or MacDougall [12]). Those terms not found in these references will be defined as needed.

One-Component Model

Thermodynamic analysis is possible only if the system under consideration exists in a state of equilibrium which is uniquely defined by a finite set of independent variables. A given mass of a perfect gas, for example, can be completely described by two variables. In the case of a non-relaxing, non-hysteretic elastic material which is under unidirectional tension, three variables, in addition to the mass, are needed. Although any three would suffice, it is most convenient for one of them to be the force per unit cross-sectional area in the direction of tension or the percentage elongation of the material in this direction, and for the other two to be T and P or T and V.

For the present purposes it is convenient for the product of tension and elongation to have the dimensions of work, as Gerke [5] has mentioned. Therefore, the quantity f will be considered to be the total unidirectional force on the material and l will be the total length of the material. These variables will be sufficient for the comparison of different states of the same piece of material, but the dimensions at some given temperature and

* Research Fellow of Textile Research Institute, Princeton, New Jersey. Present address: Jackson Laboratory, E. I. du Pont de Nemours & Co., Inc., Wilmington, Del.

pressure (or volume) of the unstrained piece are needed for the comparison of different pieces of the same mass.

In a hysteretic system, however, it is apparent that the three variables T, P, and l, for example, will not uniquely specify the magnitude of f; another variable of the system is required.

When relaxation occurs, another complicating feature is the question of the existence of thermodynamic equilibrium states. If the stress of a strained elastomer relaxes spontaneously, it is obvious that the material is not in a state of equilibrium. In nearly all real systems the same question arises to a greater or lesser degree. Mayer and Mayer [13] have discussed this point from the statistical viewpoint and have presented the concept of inhibition, which can be illustrated by the element uranium.

Even though uranium is not in equilibrium with respect to its radioactive decay, it is in equilibrium with respect to P, V, and T transitions. In such a case, the system is considered to be in equilibrium with respect to all transitions except radioactive decay, this process being eliminated from consideration by the imposition of an inhibition, and thermodynamic treatment of the other processes is then possible. The same analysis applies also to all radioactive isotopes, regardless of their half-lives. In each case, however, any measurements on the system or any cyclic transitions must be performed in time intervals very much smaller than those required for any measurable spontaneous transition of the system.

Now, the process of stress-relaxation in an elastomer is thermodynamically analogous to radioactive decay and a similar inhibition can be imposed. This inhibition can best be specified by the designation of another variable of the system—the degree of relaxation, R, which can also serve as the added variable for a hysteretic system.

The actual magnitude of the degree of relaxation cannot be specified except in a few special cases. Nevertheless, the four quantities R, T, P (or V), and l (or f) serve to define the thermodynamic state of a relaxing, hysteretic system in a unique manner. For the purposes of applying thermodynamic considerations to the system, R will be considered to be inhibited to a constant value, and it should be understood that each equation in this study has this restriction placed upon it.

Bearing in mind the preceding discussion, the equations of Wiegand and Snyder and of Elliott and Lippmann can now be derived. Consider a given mass of elastic material which has been stretched out to a length l at some given temperature T and pressure P. The tension in this substance is initially $f = f(T, P, l, R)$, but it will decay at a rate which is at first very rapid and becomes progressively slower. At constant T, P (or V), and l this relaxation of the tension can be attributed to a spontaneous change in R. At each instant, however, the magnitudes of all the properties of the system are functions of T, P (or V), l, and R, and at any given moment, when the value of R is R_a, it is possible to imagine that the system is suddenly inhibited to remain at this value of R_a while a reversible infinitesimal change in T, P (or V), and l is allowed to occur. Under these conditions the internal energy of the system changes by an amount

$$dE = q - w, \tag{1}$$

and

$$w = -f\,dl + P\,dV, \tag{2}$$

while

$$q = T\,dS, \tag{3}$$

since the transition is reversible.

Combining equations (1), (2), and (3) gives

$$dE = T\,dS + f\,dl - P\,dV. \tag{4}$$

Dividing equation (4) by ∂l and imposing the conditions of constant T and P gives

$$(\partial E/\partial l)_{TP} = T(\partial S/\partial l)_{TP} + f - P(\partial V/\partial l)_{TP}, \tag{5}$$

which becomes the Wiegand and Snyder equation if $P = 0$ or $(\partial V/\partial l)_{TP} = 0$. (Note: Although Wiegand and Snyder did not use the subscript P in their equation, they refer to Gerke [5], who is quite explicit in pointing out that the pressure is considered constant in the model used.)

If, however, T and V are kept constant after division by ∂l, then

$$(\partial E/\partial l)_{TV} = T(\partial S/\partial l)_{TV} + f, \tag{6}$$

which is the equation of Elliott and Lippmann.

Equation (5) can be rewritten in the form

$$\begin{aligned} f &= (\partial E/\partial l)_{TP} + P(\partial V/\partial l)_{TP} - T(\partial S/\partial l)_{TP} \\ &= (\partial H/\partial l)_{TP} - T(\partial S/\partial l)_{TP}, \end{aligned} \tag{7}$$

where $H = E + PV$. If, now, $F = H - TS = E + PV - TS$, then

$$dF = dE + P\,dV + V\,dP - T\,dS - S\,dT, \quad (8)$$

and equation (4), when substituted in equation (8), gives

$$dF = f\,dl + V\,dP - S\,dT. \quad (9)$$

At constant R, equation (9) is a perfect differential, and therefore

$$(\partial S/\partial l)_{TP} = -(\partial f/\partial T)_{lP}, \quad (10)$$

which, with equation (7), gives

$$f = (\partial H/\partial l)_{TP} + T(\partial f/\partial T)_{lP}. \quad (11)$$

As it stands, equation (11) is valid for all values of R, even when its rate of change is very rapid. Experimentally, however, measurements of the various terms of the equation must be carried out in time intervals of such short duration that R does not change appreciably during each measurement. This requirement can be met quite readily at nearly all R values in the determination of f, but not of $(\partial f/\partial T)_{lP}$. Consequently, in practice, the system is allowed to relax until the rate of change of R becomes sufficiently slow to enable measurement of the temperature coefficient of the tension in a time interval which is short compared to the rate of relaxation.

Wiegand and Snyder defined the quantity

$$-T(\partial S/\partial l)_{TP} = T(\partial f/\partial T)_{lP}$$

as the entropy contribution to the tension, and the difference between the tension and the entropy term was considered to be the energy contribution. As equation (11) indicates, however, this latter quantity is really an enthalpy, and not an energy, term. Meyer and Van der Wyk [15] have shown that at low pressures the magnitude of $P(\partial V/\partial l)_{TP}$ is very small compared to $(\partial E/\partial l)_{TP}$. Therefore, for all practical purposes, the energy and enthalpy terms may be considered identical; but a rigorous analysis demands a distinction between the two quantities.

Elliott and Lippmann, on the other hand, defined equation (6) as the basic one for elastic systems. From the equation for the Helmholtz free energy, analogous to equation (8), it can be shown that

$$(\partial S/\partial l)_{TV} = -(\partial f/\partial T)_{lV}. \quad (12)$$

Unfortunately, however, $(\partial f/\partial T)_{lV}$ cannot be determined directly, and Elliott and Lippmann have shown that this quantity, which they define as being $1/T$ times the entropy contribution to the stress, can be approximately evaluated from the following expression:

$$(\partial f/\partial T)_{lV} \approx (\partial f/\partial T)_{lP} + M\beta_1 A', \quad (13)$$

where M = extension modulus $= l(\partial f/\partial l)_{TP}$, $\beta_1 = 1/3$ thermal coefficient of volume expansion $= 1/3V(\partial V/\partial T)_{lP}$, and A' = anisotropy factor $= 3V/l(\partial l/\partial V)_{fT}$. (Elliott and Lippmann used $\beta = 1/l(\partial l/\partial T)_{DF}$, where D is the deformation ratio, in their equation since they were able to show that β_1 was very nearly equal to β. The anisotropy factor is written here as A' to distinguish it from the Helmholtz free energy, A.) Apparently, Elliott and Lippmann chose to define the energy and entropy terms as they did because they were able to show that data of Meyer and Ferri [14] for rubber indicated that $(\partial E/\partial l)_{TV} = 0$; therefore, this rubber was "ideal" on the basis of their definitions.

Quite obviously, the definitions of the energy and entropy components of the tension are somewhat arbitrary. Of the definitions discussed here, those of Elliott and Lippmann have the advantage of being able by themselves to account for the total tension. But, on the other hand, the experimental determination of the terms is somewhat troublesome, since β_1 is difficult to measure and A' can only be estimated. The Wiegand and Snyder definitions give the tension as the sum of three terms involving energy, entropy, and volume. As has been mentioned before, the sum of the energy and volume terms is the enthalpy factor and, in many cases, differs little from the energy term. In this case, however, even though the energy term is not exactly known, the entropy contribution can be measured directly.

Thus, each set of definitions has its favorable and unfavorable points. For many practical problems, however, the two approach identity. For example, if $(\partial V/\partial l)_{TP} = 0$ (*i.e.*, if Poisson's ratio is one-half), it can be shown that $(\partial E/\partial l)_{TP} = (\partial E/\partial l)_{TV}$ and $(\partial S/\partial l)_{TP} = (\partial S/\partial l)_{TV}$, since

$$(\partial E/\partial l)_{TP} = (\partial E/\partial l)_{TV} + (\partial E/\partial V)_{Tl}(\partial V/\partial l)_{TP} \quad (14)$$

and the second term on the right becomes zero under the above conditions. For an isotropic material, $A' = 1$. As the material becomes anisotropic, A' decreases and, in the limit, becomes equal to zero. Under this latter condition, the two equations also become identical.

For a rigorous consideration of elasticity, however, the distinction between the two definitions cannot be overlooked, and a choice between the two must be made. Since nearly all experimental work has been carried out under constant pressure conditions, it seems that the Wiegand and Snyder definitions are to be favored. The author suggests, however, that enthalpy, rather than energy, be considered the fundamental quantity. With this modification, the tension becomes a sum of only two quantities.

It has already been shown that the elastic system must be allowed to relax to some extent before a direct determination of $\partial f/\partial T$ can be made. For systems in states of rapid relaxation, an indirect determination of $\partial f/\partial T$ may be possible under certain conditions. Thus, for example, tension-elongation curves for the material can be determined at various temperatures for a finite, yet very rapid, rate of elongation. If the rate of relaxation of the material is the same at all temperatures, then the value of R at any elongation is independent of T, and the tension can then be determined as a function of T at constant l. The hypothesis that the relaxation rate is temperature-independent requires considerable study before it can be accepted as valid; and until it can be shown to be acceptable, the above procedure cannot be used.

Before extending the treatment to a two-component system, it is interesting to investigate the validity of the kinetic theory of rubber elasticity from the thermodynamic point of view.

In all of the formulations of the kinetic theory which have been published to date [3, 4, 6, 7, 9, 17], the fundamental assumptions have been that the unstrained rubber is isotropic and that the energy contribution to the tension is zero at all extensions. Consequently, the tension is due to entropy only; and, by setting up a model for the system, the entropy has been developed as a function of the elongation, from which the derivative, $\partial S/\partial l$, and hence the tension, $-T(\partial S/\partial l)$, can be evaluated. In setting up the model, however, it has generally been the practice to assume that the volume is independent of the extension—*i.e.*, $(\partial V/\partial l)_{TP} = 0$. Under this assumption, the definitions of Wiegand and Snyder and of Elliott and Lippmann become identical, as has been shown, but it remains to be seen how reasonable this assumption is.

It can readily be shown that

$$(\partial V/\partial l)_{TP} = -(\partial l/\partial V)_{fT}(\partial f/\partial l)_{TV} \times (\partial V/\partial P)_{Tl}. \quad (15)$$

The term $(\partial l/\partial V)_{fT}$ is $l/3V\,A'$ and is equal to $l/3V$ for an isotropic material and approaches zero as anisotropy appears. The second term, $(\partial f/\partial l)_{TV}$, is the extension modulus and is never zero or negative. Consequently, for an isotropic material, Poisson's ratio is one-half and $(\partial V/\partial l)_{TP} = 0$ only if $(\partial V/\partial P)_{Tl} = 0$—that is, if the material is incompressible. Quite obviously, isotropic rubbers are not incompressible; hence, the assumption that Poisson's ratio is one-half is not rigorously valid. Of course, the magnitude of $(\partial V/\partial l)_{TP}$ may be very close to zero, but it must be understood that it is not identically zero.

Furthermore, it can also be shown that

$$(\partial f/\partial T)_{lP} = -(\partial f/\partial l)_{TP}(\partial l/\partial T)_{fP}. \quad (16)$$

Since $(\partial f/\partial l)_{TP}$ is always positive, $(\partial f/\partial T)_{lP}$ must be opposite in sign to $(\partial l/\partial T)_{fP}$. Now, for an isotropic material, $(\partial l/\partial T)_{fP}$ must be positive; therefore, $(\partial f/\partial T)_{lP}$ is negative and $(\partial E/\partial l)_{TP}$, the energy contribution, cannot be zero, but must be greater than f in isotropic materials. Meyer and Van der Wyk [15] have already pointed out that rubbers at elongations of 10% and less show negative entropy terms. The above serves to explain these results.

We must conclude, therefore, that the assumptions of the kinetic theory of rubber elasticity are self-contradictory and that a new model is required. Recently, Tobolsky and Scott [16] have developed an equation in which the energy contribution is not neglected. This equation was derived for the purpose of explaining second-order transitions, but it may also prove sufficient to resolve the above inconsistencies.

Equation (16) suggests another method for measuring $(\partial f/\partial T)_{lP}$. The quantity $(\partial l/\partial T)_{fP}$ can be

readily determined by hanging a weight on the material under study, allowing the material to creep to nearly constant length, and then observing the change in length of the sample as the temperature is changed. At the same time, the modulus, $(\partial f/\partial l)_{TP}$, can be measured by the pulse-propagation technique of Hamburger [8].

In the following section the two-phase system of an elastomer in contact with a one-component swelling agent will be considered. Equations for constant P and constant V conditions will be derived, although the former gives an equation which is experimentally simpler and theoretically more logical.

Two-Component Model

The system under consideration will be assumed to consist of a homogeneous solid phase made up of elastomer plus adsorbed swelling agent and a liquid phase of swelling agent only. As before, it is also assumed that all transitions of the system are reversible ones; therefore, the chemical potential of each component will be the same for both phases. Since the liquid phase contains only swelling agent, the chemical potential of the elastic substance is of no interest.

Consider, now, the solid elastic phase only, maintained at some value of T, P (or V), l, R, and n, where n is the amount of swelling agent present in the solid phase. For any imaginary, infinitesimal, reversible change in T, P (or V), l, and n, the change in the internal energy of the phase is

$$dE = q - w + (\partial E/\partial n)\,dn, \qquad (17)$$

where $(\partial E/\partial n) = \mu$, the chemical potential of the swelling agent in the solid phase.

Substituting equations (2) and (3) in equation (17) gives

$$dE = T\,dS - P\,dV + f\,dl + \mu\,dn. \qquad (18)$$

Dividing equation (18) by ∂l, imposing conditions of constant T, P, and n, and rearranging gives

$$f = (\partial E/\partial l)_{TP_n} - T(\partial S/\partial l)_{TP_n} + P(\partial V/\partial l)_{TP_n}$$
$$= (\partial H/\partial l)_{TP_n} - T(\partial S/\partial l)_{TP_n}, \qquad (19)$$

which is the two-phase analog of equation (7). The analog of equation (6) is obtained by dividing by ∂l and imposing constant T, V, and n conditions:

$$f = (\partial E/\partial l)_{TV_n} - T(\partial S/\partial l)_{TV_n}. \qquad (20)$$

From the expressions for the Gibbs free energy, F, and the Helmholtz free energy, A, it can be shown that

$$-T(\partial S/\partial l)_{TP_n} = T(\partial f/\partial T)_{lP_n} \qquad (21)$$

and

$$-T(\partial S/\partial l)_{TV_n} = T(\partial f/\partial T)_{lV_n}. \qquad (22)$$

Equation (21) gives the entropy contribution to the tension as defined by Wiegand and Snyder, while equation (22) gives the term defined by Elliott and Lippmann; but, unfortunately, neither one can be determined directly, since a change in T will, in general, cause a concomitant change in n, and the experimental determination of the temperature coefficient of the tension can be carried out at constant l and P only.

If, at constant R, the tension is a function of T, P, l, and n, a differential change in the tension is given by

$$df = (\partial f/\partial T)_{Pln}dT + (\partial f/\partial P)_{Tln}dP$$
$$+ (\partial f/\partial l)_{TPn}dl + (\partial f/\partial n)_{TPl}dn. \qquad (23)$$

Divide equation (23) by ∂T, maintaining l and P constant, and rearrange:

$$(\partial f/\partial T)_{lP_n} = (\partial f/\partial T)_{lP}$$
$$- (\partial f/\partial n)_{TPl}(\partial n/\partial T)_{lP}. \qquad (24)$$

Multiplication of equation (24) by the temperature gives the Wiegand and Snyder entropy term, $T(\partial f/\partial T)_{lP_n}$, as the sum of two quantities. The first of these quantities, $T(\partial f/\partial T)_{lP}$, is the experimental temperature coefficient of the tension times the temperature, while the second term is the correction to account for the temperature effect on swelling. This correction term is the product of temperature, the differential $(\partial f/\partial n)_{TPl}$, which is the equivalent of the equation for the hair hygrometer, and the experimentally determinable temperature coefficient of n, $(\partial n/\partial T)_{lP}$, and should not be difficult to measure.

If the Elliott and Lippmann definitions are accepted as standard, the resultant equation is somewhat more complicated. It can be shown that

$$(\partial f/\partial T)_{lV_n} = (\partial f/\partial T)_{lP_n}$$
$$+ (\partial f/\partial P)_{lT_n}(\partial P/\partial T)_{lV_n}. \qquad (25)$$

The first term on the right side of equation (25) is given by equation (24); and, through the use of a method involving approximations very similar to those used by Elliott and Lippmann in deriving equation (13), it can be shown that

$$(\partial f/\partial P)_{lTn}(\partial P/\partial T)_{lVn} \approx [(\partial f/\partial l)_{pTn} - (\partial f/\partial n)_{TPl}(\partial n/\partial l)_{TPn}] \times [(\partial V/\partial T)_{lP} - (\partial V/\partial n)_{TPl}(\partial n/\partial T)_{lP}] \times (\partial l/\partial V)_{fTn}. \quad (26)$$

The first bracketed term is the two-component analog of M; the second corresponds to β_1; and the term $(\partial l/\partial V)_{fTn}$ is the equivalent of the anisotropy factor, A'.

As has been pointed out in the preceding section, the Wiegand and Snyder definition is to be preferred over that of Elliott and Lippmann for theoretical reasons. Even more important from the practical viewpoint is the relative simplicity of the corresponding Wiegand and Snyder equations (equations (19), (21), and (24)) compared with those of Elliott and Lippmann (equations (20), (22), (24), (25), and (26)).

Summary

Although true thermodynamic equilibrium is not obtainable in hysteretic, relaxing elastic systems, a thermodynamic analysis of the stress can be undertaken. Such an analysis shows that the stress is given by the sum of two terms, whether in the case of the one-component or the two-component system.

If temperature and volume are considered to be independent variables of the system, the stress is found to be attributable to an entropy term and to an internal energy contribution. At the present time, however, experimental techniques make temperature and pressure the independent variables, and the stress is then separable into an entropy term and an enthalpy term. It is suggested that this latter analysis be taken as the standard.

The equations for the one-component system have been reviewed and, by a logical extension, have been carried over to the two-component system.

Finally, the fundamental assumptions of the present-day kinetic theory of rubber elasticity have been shown to give results which are self-inconsistent.

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Some Replica Techniques Useful in Electron Microscopy of the Surface of the Wool Fiber

K. Rachel Makinson

Division of Physics, Commonwealth Scientific and Industrial Research Organization, Sydney, Australia

Abstract

Techniques have been developed for making replicas, suitable for examination in the electron microscope, of the surface of the wool fiber without subjecting the fiber to heat or pressure. Electron micrographs are reproduced to illustrate the appearance of normal wool fibers and of fibers subjected to various chemical and mechanical treatments. The results obtained support the view that the scales consist of a smooth layer overlying a more resistant furrowed structure. Certain other features of the scales, including a peculiar "fringed" edge, are also noted.

ALTHOUGH SOME STUDIES of the cuticle of wool have been made by direct examination in the electron microscope (see bibliography given by Swerdlow and Seeman [17]; also [9, 10, 19]), its thickness is such that the details of its surface structure are best studied by replica techniques. At the time when this investigation was begun, the techniques which had been developed [2, 7] involved subjecting the fiber simultaneously to high temperature and pressure, which treatment could introduce artifacts into the replicas. The techniques used in the work reported here were designed to avoid this. While the investigation was in progress, Swerdlow and Seeman [17] published some electron micrographs of replicas obtained by another technique which was comparatively simple and rapid. However, in this case the fiber was subjected for 20 min. to a temperature of 90°C and to a pressure which, although less than that used previously, was still considerable.

The methods described below do not involve such treatment and consequently reduce the risk of artifacts. In general, the results obtained agree with those obtained by Swerdlow and Seeman, indicating that the features noticed by them are not artifacts; a few additional features are described.

Experimental Procedure

(1) The Instrument

The electron microscope available for this study was an R.C.A. Console model, type EMC2, which has an accelerating voltage of 30 kv. An objective aperture was used throughout. All photographs were made at a magnification of about 500 times (the exact magnification depending on the focusing current) and enlarged to 2,000 or 3,000 times for study. They are reproduced here at about 1,900 times.

In the reproductions, the wires of the specimen screen have been masked to reduce flare.

(2) General Considerations in the Choice of Replica Technique

As mentioned above, it was desired to avoid applying heat and pressure to the fibers. The safest method seemed to be to make a negative replica by using a solution which wetted the fiber. This immediately introduced the difficulty that surface tension causes the liquid to climb up around the fiber, so that extremely thick regions are left after the solvent has evaporated (see Figures 1(*a*) and 1(*b*)). Such a replica has obvious disadvantages. A two-stage process, which will eliminate these very thick regions, is therefore necessary. Two techniques have been developed and are described below.

(3) Collodion-Silica Replicas (Figures 2-4, 6-10)

In principle, this is a standard technique, which has been modified in detail for this particular problem. The negative collodion replicas are made from 1% collodion solution on a microscope slide, and have the forms shown in Figures 1(*a*) and 1(*b*). Silica is evaporated onto these in a vacuum; from 5 to 10 mg. of silica at a distance of 8.5 cm. has been found to be satisfactory. Since on coarse structures the

silica tends to form a film of uniform thickness normal to its surface [4], the resultant positive replica shows considerably less variation in thickness than the original negative one (see Figure 1(*c*)).

Such silica replicas may be considered, to a first approximation, as giving a differential picture of the coarse surface structure, since they appear thick on steeply inclined regions and thin on flat regions [18]. On finer structure they give a normal picture [4]. Their contrast, for 30-kv. electrons, is fairly good and can be improved by gold-shadowing at either the collodion or the silica stage (Figure 8).

It is usually found convenient to wet-strip the collodion replicas onto specimen screens before depositing the silica. Severe overhang at the collodion stage is to be avoided, as it causes the silica to deposit as shown in Figure 1(*d*), so that the center falls out of the silica replica when the collodion is dissolved off.

(4) *Gelatin-Collodion Replicas (Figure 5)*

This method is capable of giving very detailed replicas, but has been found to be unsuitable for use with the microscope used in this study because of the high stopping power of collodion for low-voltage (30-kv.) electrons. Because it appears that the method should be useful with higher voltages, it is described here.

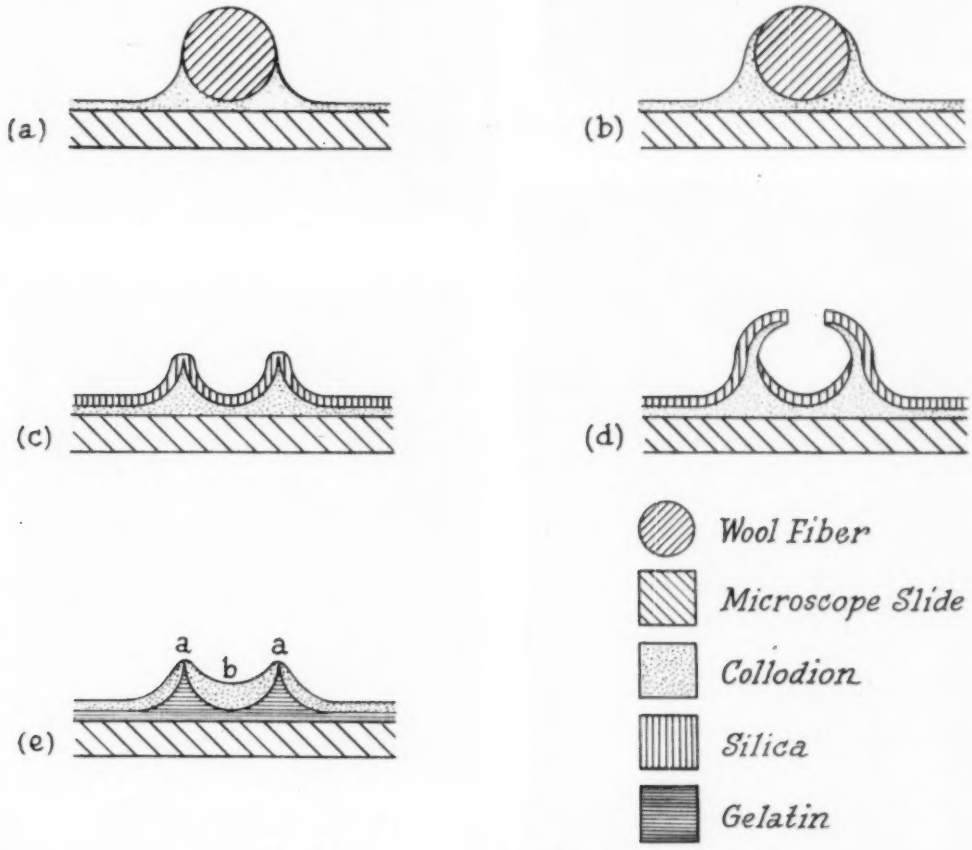

FIG. 1. *The formation of one- and two-stage replicas.*

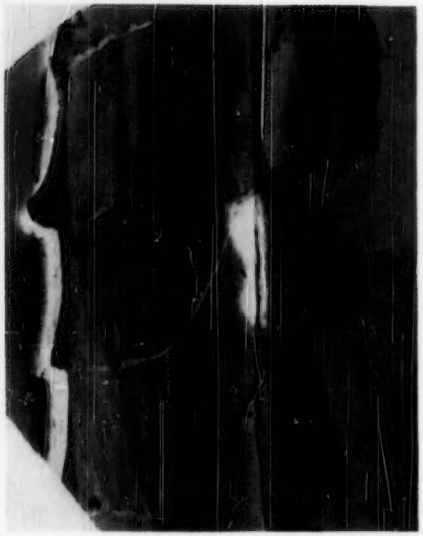

FIG. 2. *Collodion-silica replica of a normal wool fiber.*

FIG. 3. *Collodion-silica replica of a normal wool fiber.*

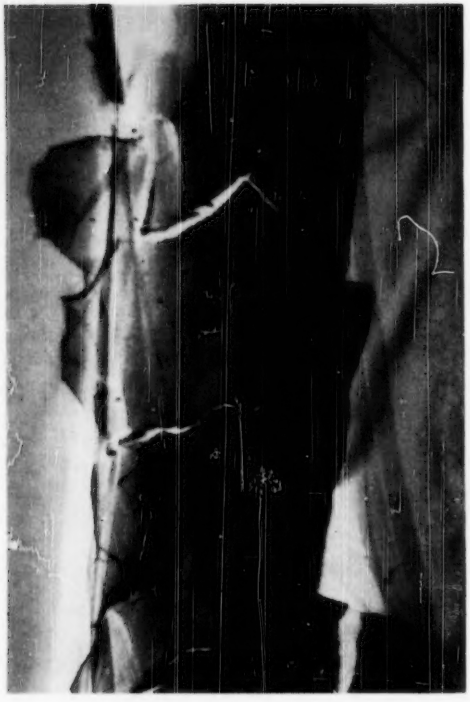

FIG. 4. *Collodion-silica replica of a normal wool fiber.*

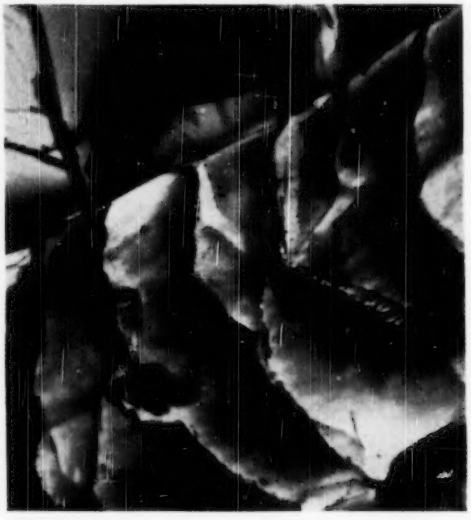

FIG. 5. *Gold-shadowed gelatin-collodion replica of a normal wool fiber. Positive print.**

* Since the stopping power of the collodion (or silica in Figure 8) replica is comparable with that of the gold layer, nothing is gained by reversing the print.

FIG. 6. *Collodion-silica replica of a wool fiber treated with alcoholic KOH.*

FIG. 8. *Gold-shadowed collodion-silica replica of a wool fiber, wet-chlorinated at pH 4 for 9 min.; shadowed at the collodion stage. Positive print.**

FIG. 7. *Collodion-silica replica of a wool fiber treated with alcoholic KOH.*

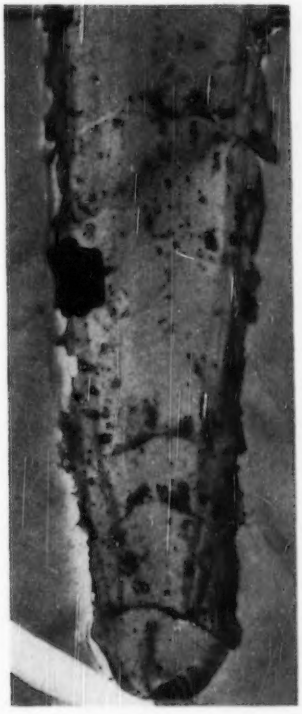

FIG. 9. *Collodion-silica replica of a wool fiber wet-chlorinated at pH 4 for 1 min.*

Two slightly different methods have been developed. In the first, the negative replica is made in 5% or 10% gelatin spread on a microscope slide which previously had been smeared with a hydrophobic substance such as cetyl alcohol. The gelatin is allowed to dry out to equilibrium with the atmosphere before the fiber is removed. The surface tension effects discussed in section (2) are very severe. The positive replica is then made with ¾% or 1% collodion solution. The desired portions of the replicas are marked out with scratches, the double film is removed from the slide and placed on the surface of cold water with the gelatin side down, and the gelatin is allowed to swell. Hot water is then introduced to dissolve the gelatin, and the positive collodion replicas are picked up on specimen screens. They may subsequently be gold-shadowed.

The alternative method, which is easier, replaces the gelatin by 3% glycerin jelly, as used by Manby [12] for optical microscopy. With this, the slide need not be hydrophobic, because the collodion film may be floated off by lowering the microscope slide obliquely into warm water, which rapidly dissolves the jelly. This material gives a smoother film than pure gelatin; it may be allowed to dry out to equilibrium with the atmosphere before placing the fibers on it, and their impressions can then be obtained simply by breathing on the jelly to moisten it. Since it loses this slight amount of moisture fairly quickly, it does not creep up so far around the fibers as pure gelatin does.

Since polymer solutions tend to give a film with a flat upper surface [5], the resultant positive collodion replica still exhibits considerable variation in thickness, as shown in Figure 1(*c*). The very thin regions, *a*, often split in the electron beam, while the regions *b* are too thick for penetration by 30-kv. electrons. The great variation in thickness may also sometimes cause the replica to flatten out, thus exaggerating the diameter of the fiber.

Figure 5 shows a gold-shadowed replica prepared by the former of these two methods. Fewer than 1% of these replicas had a thickness range suitable for examination by 30-kv. electrons.

Results

Except in the case of the Chlorzymed fibers, 60's Merino wool was used in this study. Fibers subjected to the following treatments were examined:

(i) Normal wool, extracted with aqueous detergent solution followed by ether (Figures 2-5).

(ii) Wool, treated by the Freney-Lipson [3] alcoholic alkali anti-felting process (Figures 6 and 7) —*i.e.*, immersion for 1 min. in a solution of 7% caustic potash and 1% water in ethyl alcohol, with subsequent neutralization by aqueous sulfuric acid, followed by washing with water.

(iii) Wet-chlorinated wool (Figures 8 and 9): treatment with a sodium hypochlorite solution containing 0.01% available chlorine and a total of 4% chlorine (based on the weight of the wool) (*cf.* Speakman [16] and Alexander [1]) at pH 4 and at pH 8; varying times of treatment. (The low concentration of chlorine was chosen in the hope of achieving uniformity of treatment.)

(iv) Chlorzymed wool (Figure 10). This was an English wool, not Merino, treated in England by dry-chlorination, followed by papain [6].

(v) Mechanically abraded wool. Individual taut fibers were rubbed to and fro 20 times under a load of 0.1-g. weight against a surface of polished horn (apparatus described by Mercer and Makinson [13]).

FIG. 10. *Collodion-silica replica of a Chlorzymed wool fiber.*

The commercial finishing treatments (ii) and (iii), described above, were chosen not only because of their practical interest but also because they are known to produce big changes in some of the properties of wool—such as felting—without producing any marked change in its structure, as seen in the optical microscope; (iv) was chosen as an example of a more drastic treatment producing similar effects; (v) was chosen in order to see whether very light abrasion would produce results similar to those obtained by Swerdlow and Seeman [17] by heavy abrasion.

The results obtained may be summarized as follows:

The scales of normal, undamaged wool are smooth and rather featureless, but show traces of longitudinal striations, which are especially clearly revealed by the gelatin-collodion technique. Some of the scales have "fringed" edges, shown clearly in Figures 5 and 8, which usually are visible only as "double" edges in the less contrasty, unshadowed collodion-silica replicas.

Wool treated by methods (ii), (iii), and, in many cases, (v) appears to be "etched," removal of a less resistant, smooth layer revealing a prominent longitudinal structure. "Double" and "fringed" edges become more frequent. The scales are in general still clearly defined, although in some cases even very brief wet-chlorination has been found to remove them completely over limited regions (Figure 9), revealing in the original negative a granular rather than a striated structure (*cf.* [17, Figure 4]). (The large dark specks in Figure 9 are dirt which was apparently not completely removed from the fiber.) A particular structure, which will be referred to as a "seam," is often visible (*e.g.*, *A* in Figure 7).

Chlorzymed wool is devoid of scales. The prominent longitudinal striations, which are of an order of magnitude coarser than those proper to the scales, appear to be cortical cells exposed or nearly exposed by the treatment.

Discussion

At one time it was thought possible that the longitudinal striations on the scales, reported by earlier workers [2, 17], might have been artifacts caused by the heat and pressure applied to the fiber during the preparation of the replicas. The techniques used here, however, have shown the same striation without such treatment, and it therefore appears to be an integral part of the structure. In general, this work supports the conclusion reached by earlier workers [14, 17] that the wool scale consists of an underlying longitudinal structure covered by a smooth and rather featureless layer, which is chemically and mechanically the less resistant of the two. These replica techniques do not give any information as to the existence of thin membranes either above [9, 10] or below [8] the scales. Although this work has shown (Figure 9) that there is a comparatively smooth layer lying between the cuticle and the cortex, somewhat similar to that found by Swerdlow and Seeman [17], this may be merely the residue of the resistant portion of the scales.

The "fringed" edge to the scales has not been reported previously, although some of Swerdlow and Seeman's unpublished electron micrographs show it. It may be a continuation of the longitudinal structure, exposed at the edges where damage is more likely to occur, but the limited data obtained in this study suggest that it is of a somewhat coarser structure.

The "seams," which are more prevalent after chemical attack, are probably due to overlapping of the lateral edges of the scales (*cf.* [15, Figure 16]). It has already been suggested [11] that this type of anti-felting treatment weakens the scales; it is now suggested that, as a result of this weakening, the upper portion of the overlap may sink over the lower so that a "step" is formed and the "seam" becomes visible.

Acknowledgments

The author wishes to thank the following: the Sydney Technical College, whose electron microscope was used for this investigation; Mr. R. S. Millet, for advice on photographic technique; Mr. J. W. Pearce, for assistance with the evaporation techniques; Mr. W. R. Middlebrook of The University, Leeds, for Chlorzymed fibers; Miss J. C. Griffith and Mr. V. Burgess, for general assistance; and Mr. M. Swerdlow of the National Bureau of Standards (U.S.A.), for permission to refer to unpublished work.

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Theoretical Considerations and Measurements with Regard to the Longitudinal Abrasion of Rayon Filaments

V. E. Gonsalves

Research Laboratory, A. K. U. and Affiliated Companies, Arnhem, Holland

Introduction

The longitudinal abrasion of a rayon filament can be achieved in a very simple way. The filament is laid around a rotating roller under a certain tension. The time which passes until the filament breaks can then be determined. This time is a measure of the resistance to longitudinal abrasion.

Starting from certain simple theoretical assumptions we have derived a formula indicating the relationship between the time of abrasion until break, t, and the load on the thread. It was found, however, that this formula did not correspond with the experimental results. This meant that during this experiment the wearing-off process did not take place in the simple way which had been assumed originally.

The abrasion process was then examined more exactly. Finally, a formula was obtained indicating the relationship between time of abrasion until break and load on the thread in a way which was in far better agreement with the experiment, although this formula must not be considered to be completely accurate.

In Part I we derive the simple formula for determining the time of wearing until break, t, as an introduction to the derivation of the improved formula for determining t which is discussed in Part II. In any case, the latter formula gives a clear picture of the initial phenomena during this abrasion process. It will appear that the abrasion process is so complicated that it is hardly possible to derive an exact formula for t.

In Part III some measurements are discussed which have been carried out on threads spun with increasing stretch. They show what factor is primarily responsible for the increasing resistance to abrasion of threads spun with increasing stretch.

Part I

For the sake of clarity, we shall first give the derivation of the formula for the course of the tension in a thread which had been laid around a roller, although this derivation may be generally known.

Let us consider a single, homogeneous thread of uniform thickness which has been laid around a roller under a tension P_0 (see Figure 1).

Let the angle of wrap be α_0, the direction of rotation of the roller be that indicated in the figure, and the angular velocity of the roller be ω.

Let us consider the thread element dl and the forces exerted upon it.

Then:

$K_1 = (P + dP)\cos d\alpha \sim P + dP;$

$K_2 = (P + dP)\sin d\alpha \sim (P + dP)\, d\alpha \sim P d\alpha.$

Thus, the perpendicular pressure on dl is $Pd\alpha$. This perpendicular pressure causes a frictional force $\mu P d\alpha$, which is equal and opposite to dP:

$$dP = \mu P d\alpha.$$

The solution of this differential equation reads:

$$P = P' e^{\mu\alpha}. \qquad (1)$$

It must be remembered that in the derivation μ is assumed to be constant; thus, μ is independent of P. This is the *first assumption*.

We saw that a perpendicular force $= Pd\alpha$ is exerted on dl. The greatest perpendicular force occurs at $\alpha = \alpha_0$ (point a in Figure 1). At this point the perpendicular force on dl is equal to $P_0 d\alpha$. Here is exerted per unit of length of the thread a perpendicular force

$$P_0 \frac{d\alpha}{dl}.$$

Now, $d\alpha = \dfrac{dl}{R}$; thus, the perpendicular force per unit of length at point a in Figure 1 ($\alpha = \alpha_0$) is

$$\frac{P_0}{R}. \qquad (2)$$

When two threads are to be compared for their wearing properties, it is obvious that one must cause them to move under the same perpendicular pressure over the abrasive surface. Expression (2) shows that the situation indicated in Figure 1 meets this requirement. When the roller rotates in the opposite direction, it is not possible to conform to this requirement. In this case the highest tension in the thread would occur at b (Figure 1). At this point the tension is $P_0 e^{\mu\alpha_0}$. This tension gives a perpendicular pressure of the thread on the roller (per unit of length of the thread) which is equal to $\dfrac{P_0}{R} e^{\mu\alpha_0}$. Thus, for two threads with different frictional coefficients, μ, this perpendicular pressure becomes different.

At a (Figure 1) the highest perpendicular force

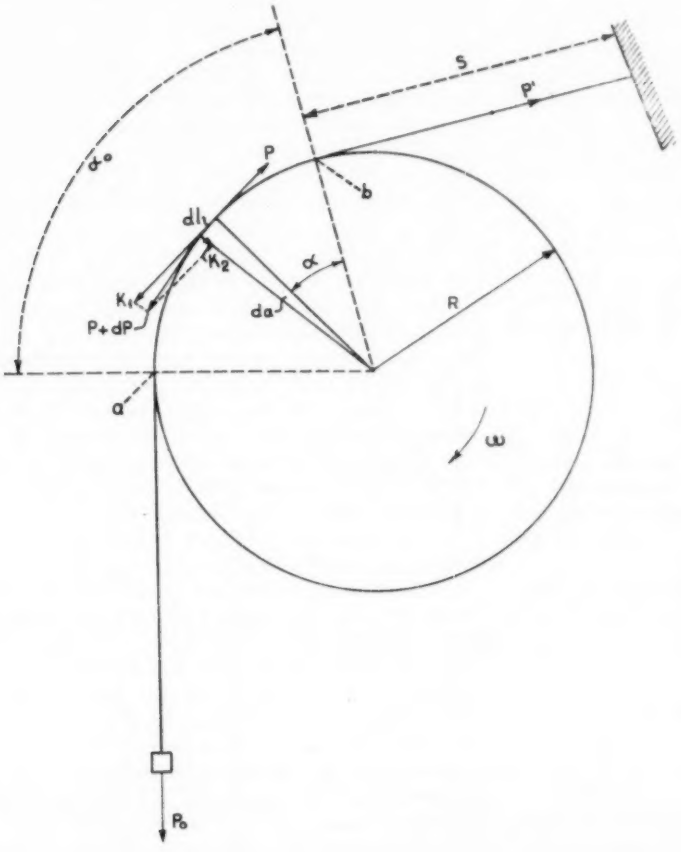

FIG. 1.

per unit of length occurs, and, consequently, the highest frictional force per unit of length:

$$\mu \frac{P_0}{R}.$$

Thus, the greatest wear of the thread will occur at a, and at this place the thread will break. The work, which is done by the friction, is force × distance. At an angular velocity ω of the roller the distance l covered per sec. is

$$l = R\omega.$$

Thus, the frictional work A carried out per sec. per unit of length of the thread at a amounts to:

$$A = \mu \frac{P_0}{R} R\omega;$$

$$A = \mu P_0 \omega. \qquad (3)$$

As we see, the frictional work is proportional to P_0. For $P_0 = 1$ g., this frictional work is equal to $\mu\omega$.

Suppose the cross section of the thread at a decreases by σ_1 cm.^{2} per sec. when $P_0 = 1$ g. With this assumption an abrasion constant (σ_1) has been introduced which is characteristic for the thread. At a per sec., σ_1 cm.^{3} of material is worn away per unit of length. For this, $\mu\omega$ g.cm. are required. The useful effect, η, of the frictional work required for the wearing-off of the thread can be expressed by the formula:

$$\eta = \frac{\sigma_1}{\mu\omega} \text{ cm.}^3/\text{g.cm.} \qquad (4)$$

Now let us assume that η is a constant quantity (η is independent of P_0—a *second assumption*). In that case the decrease in cross section per sec. will amount to $P_0\sigma_1$ cm.^{2} when the tension on the thread is P_0 g.

If at the beginning of the experiment the cross section of the thread $= O$, after t sec. it will amount to:

$$O - t \cdot P_0 \cdot \sigma_1.$$

Then the tension in the thread will be:

$$\frac{P_0}{O - t \cdot P_0 \cdot \sigma_1}.$$

If the initial force to break the thread (breaking force) is P_B, then the force required per unit area to break the thread ("strength") is $\frac{P_B}{O}$. We shall assume that this strength remains the same during the abrasion (*third assumption*). The thread will break when the tension in the thread becomes equal to the strength; thus, the time of wearing-off until break, t, is determined by the equation:

$$\frac{P_0}{O - t \cdot P_0 \cdot \sigma_1} = \frac{P_B}{O};$$

$$t = \frac{O}{\sigma_1}\left[\frac{1}{P_0} - \frac{1}{P_B}\right]. \qquad (5)$$

This simple formula indicates the relationship between the time of wearing-off until break, t, and the wear susceptibility, σ_1 (this is the mass worn away per unit of length of the thread per unit of time at a load $P_0 = 1$), and the absolute tensile strength, P_B, of the thread.

In order to prevent as far as possible the occurrence of error during the measurement of abrasion in consequence of the elongation caused by P_0 and the additional elongation caused by the abrasion itself, the following measures can be taken, the object of which is to keep the point on the thread where the abrasion is greatest as nearly as possible at the same place:

1. The angle of wrap α_0 must be as small as possible. This includes the important advantage that, in case of a slight eccentricity of the abrasive roller, the occurrence of any resonance vibrations of the load P_0 in the direction of the thread, as a result of which additional forces besides P_0 are exerted on the thread, is appreciably opposed.

2. The radius R of the roller must be small. The frictional work remains constant because this is independent of R (see formula (3)).

3. The distance S (see Figure 1) from the roller to the fixed clamping-in point must be small.

4. The operations must take place with "dry" threads, because the resulting elongation is much less in them than in "wet" threads.

In order to be able to verify formula (5) experimentally, we had to use an abrasive roller which, at least for a relatively large number of measurements with dry threads, had constant or almost constant abrasive properties. It was found that an abrasive roller covered with diamond-bort was suitable for this purpose. The diamond-bort had been incorporated in a binding agent, which re-

sulted in a layer with a thickness of about 1.5 mm. The length of the abrasive roller was 30 mm. The radius was 3.96 mm. Preliminary measurements showed that the abrasive properties of this roller were not entirely constant. The roller caused a varying wear, but the values fluctuated around an average value.

During the experiments the angle of wrap amounted to about 20°. The number of revolutions of the roller was 2,850 per min. During the abrasion the thread was subjected to a traverse motion of some millimeters in the axial direction of the abrasive roller.

For the measurements, individual filaments were used in order to keep as far as possible in agreement with the theory. For this purpose we used an arbitrarily chosen filament of 2.5 den., 100/40 unfinished luster yarn. This yarn, which came from the normal production of the pilot plant, had a dry strength of 247 and a dry elongation of 18%. The following loads (P_a) were applied: 3.5, 3.25, 3, 2.75, 2.50, 2.25, 2, 1.75, 1.50, 1.25, and 1 g.

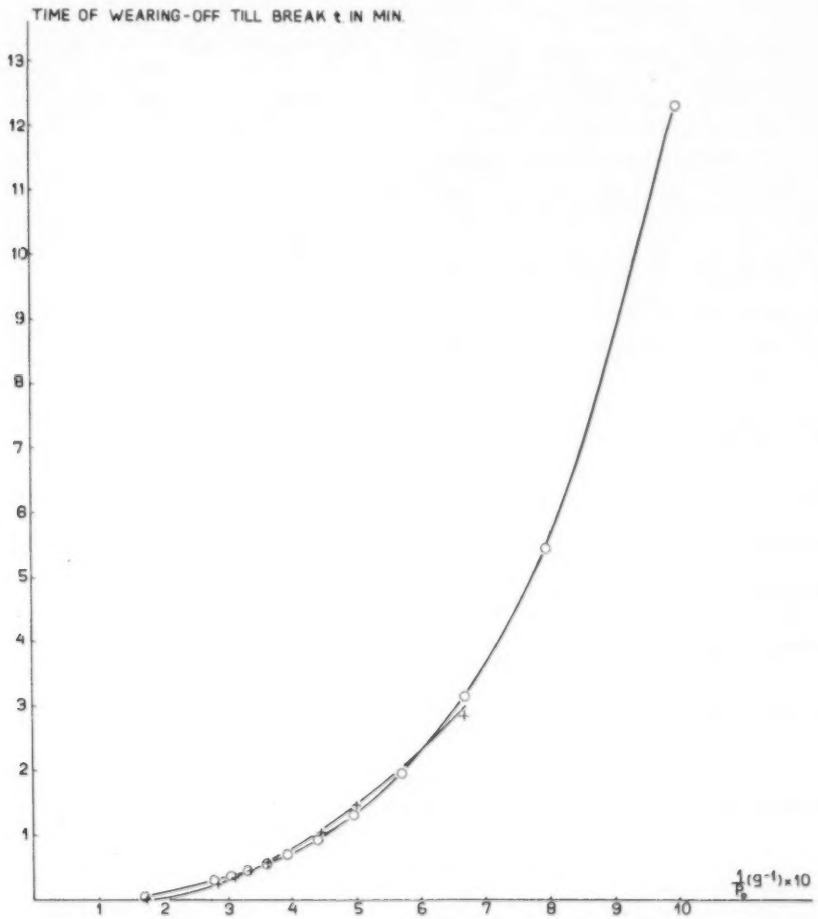

FIG. 2.

The results of two series of measurements on the same type of yarn are given in Figure 2.

According to formula (5), t as a function of $\frac{1}{P_0}$ should be represented by a straight line. We see, however, that the experiment does not give this result.

So, we had to conclude that exactly what happens during the abrasion certainly does not take place in such a simple way as had been assumed in the derivation of formula (5).

Part II

For the derivation of the formula $P_0 = P'e^{\mu\alpha_0}$ it had been assumed that μ would be independent of P. After further investigation it was found desirable to go more precisely into this matter.

The measuring arrangement is shown in Figure 3. With the aid of the tensiometer M, the tension P' was measured at various relatively small angles of wrap α_0.

If the formula $P_0 = P'e^{\mu\alpha_0}$ were valid for these situations, log P' as a function of α_0 should be represented by a straight line.

The results of these measurements are given in Figure 4.

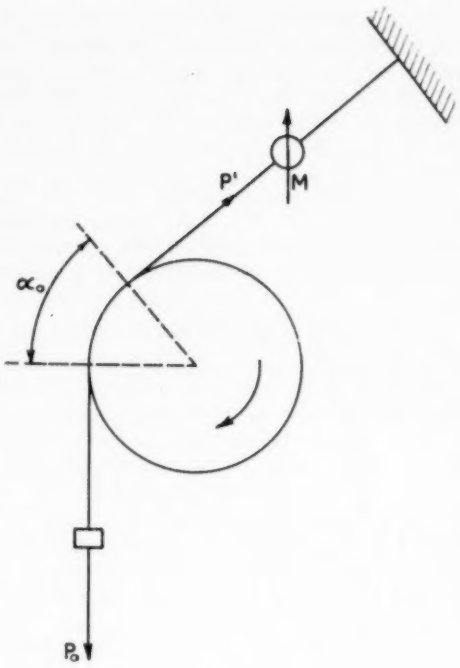

FIG. 3.

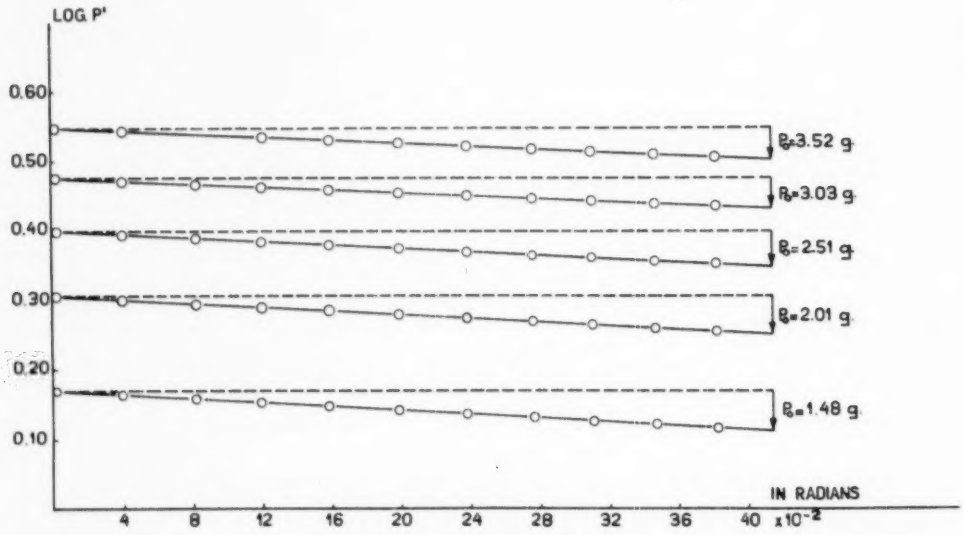

FIG. 4.

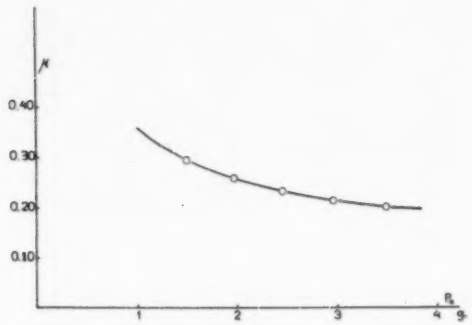

FIG. 5.

We see that the functional relationship between log P' and α_0 is linear, indeed. From this graph (Figure 4) μ was calculated as a function of P_0 (see Figure 5). We see that μ is *not* a constant, and that it is dependent upon P_0.

This does not conflict with the validity of the formula $P = P'e^{\mu\alpha_0}$ for small angles of wrap because in this case P' is only a little smaller than P_0. When α_0 = about 35°, P' is only about 10% smaller than P_0. With this slight, gradual variation of the thread tension over the roller, μ remains practically constant, which experimentally resulted in the linear relationship between log P' and α_0.

Our first assumption, that μ is essentially independent of the thread tension, is, however, not correct.

In order to gain a better insight into the phenomena occurring during the longitudinal wearing-

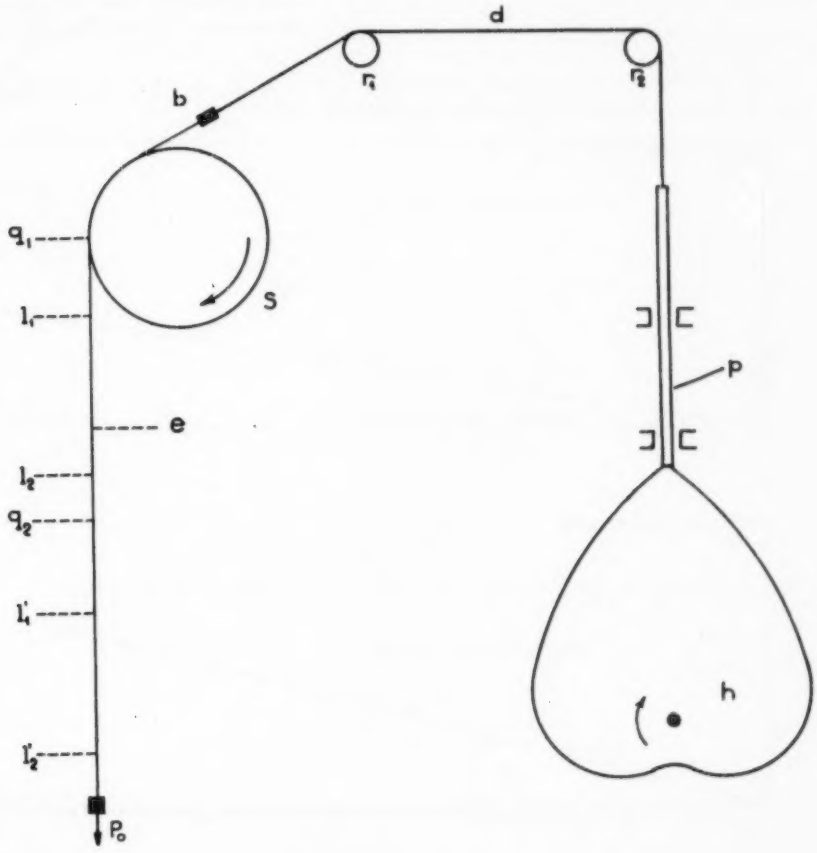

FIG. 6.

off, the experiment was carried out in a somewhat modified way.

The measuring arrangement is shown schematically in Figure 6. A normal rayon thread d (300/60) is led over two frictionless rollers, r_1 and r_2, and is fixed to a rather strong pin, p, which rests on a heart-shaped cam, h. At b a small aluminum plate of negligible weight (20 mg.) is fixed to this thread.

The filament under examination, e, which at b is fixed to the aluminum plate by means of a piece of cellophane adhesive tape, runs over the abrasive roller, S, and is kept tight by the load P_0. The filament, e, is moved up and down over the abrasive roller, S, at a constant number of revolutions of the cam, h. The velocity of the thread, e, in the up-and-down direction is constant. In this way the filament is worn away regularly over a certain length, which is determined by the dimensions of the cam. It can be expected that the thread will wear away more quickly at the reversing points of the movement (q_1 and q_2 in Figure 6).

Thus, for the examination of the worn-away portion of thread, e, we confine ourselves to the part l_1l_2. After the experiment is finished, the part of the thread l_1l_2 is cut off and examined vibroscopically for denier. After this the strength is determined on the Heim apparatus.* In order to indicate the decrease in denier and strength caused by the wear, the denier and strength of the part l_1l_2 are compared with the denier and strength of another not-worn-out part of the *same* experimental thread —*viz.*, the part $l'_1l'_2$.

TABLE I

P_0 (g.)	Time of abrasion (min.)	Decrease in den. (%)	Decrease in strength (%)	No. of determinations
2.52	0.37	1.2	4.4	20
2.52	1.1	2.9	6.4	30
2.52	1.83	8.4	6.1	30
2.52	2.55	6.6	15.0	30
2.52	3.3	9.4	22.6	30
2.52	4.0	12.8	17.3	30
2.52	5.4	15.2	17.1	20

* Gonsalves, V. E., TEXTILE RESEARCH JOURNAL 17, 369 (1947).

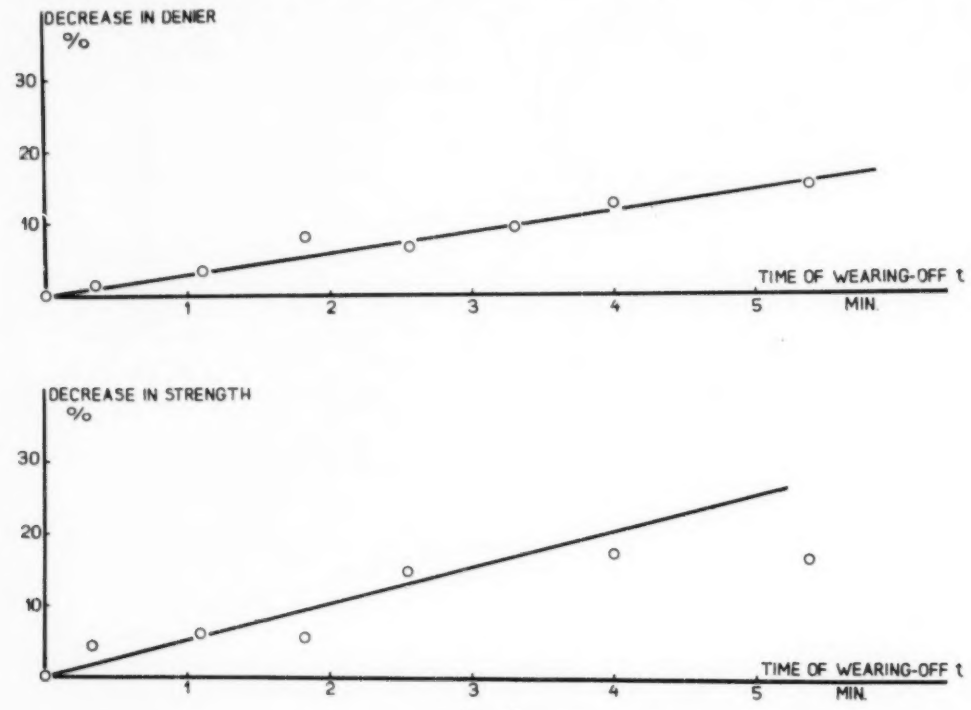

FIG. 7.

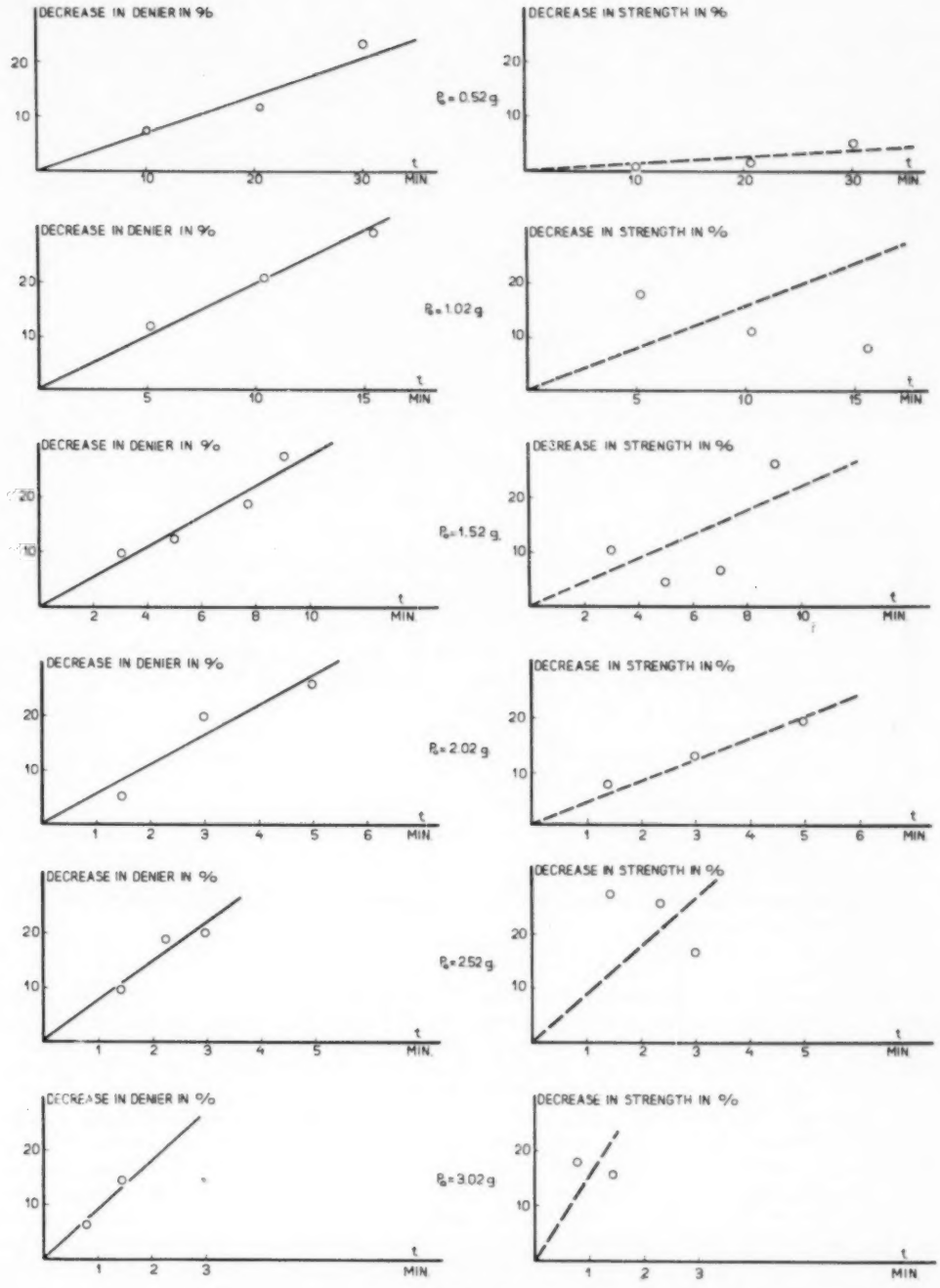
DECREASE IN DENIER IN %
DECREASE IN STRENGTH IN %
P_0 = 0.52 g
P_0 = 1.02 g
P_0 = 1.52 g
P_0 = 2.02 g
P_0 = 2.52 g
P_0 = 3.02 g
t
MIN

FIG. 8.

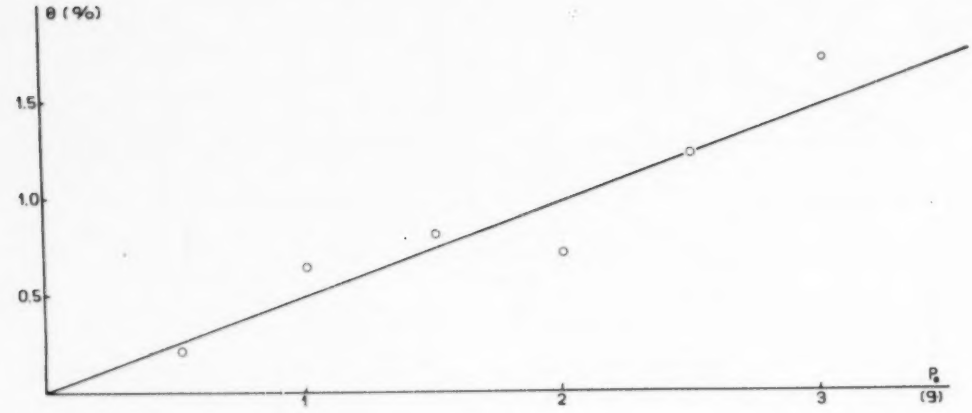

FIG. 9.

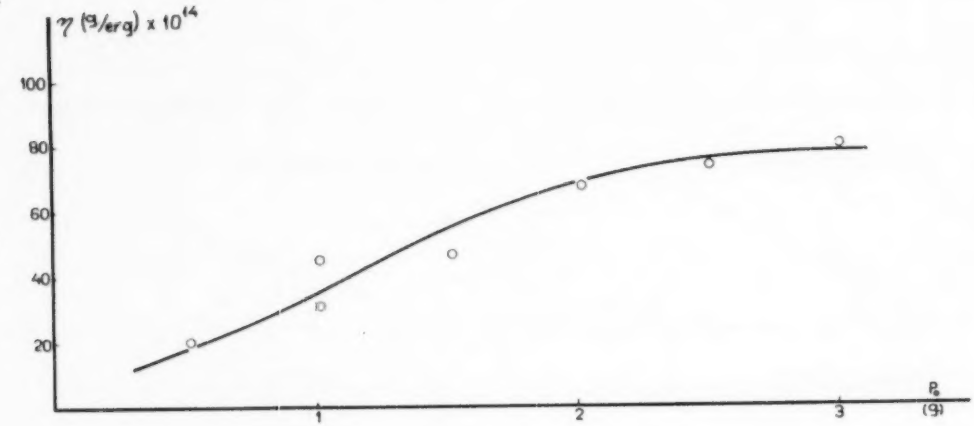

FIG. 10.

By performing many measurements in this way we obtained a survey of the percentage decrease in denier and the percentage decrease in strength during the time of wearing-off, t, of the filament. (By "strength" of a thread is meant the "relative strength" expressed in g./100 den.)

It must be remembered that during the abrasion the thread is subjected to a traverse motion of some millimeters on the abrasive roller, S (not shown in Figure 6). This motion as well as the motion caused by the cam takes place relatively slowly. The velocities are negligibly small with respect to the peripheral speed of the abrasive roller, S.

During the first measurements carried out in this way the load, P_0, was kept constant. P_0 was equal to 2.52 g., the examined portion of the thread was 2.5 den. (2-bath—60% of stretch). The results of the measurements are given in Table I.

In order to prevent the measurements from becoming too prolonged, none were carried out which would have enabled a correction for any possible alterations in abrasive properties of the abrasive roller, S. In consequence of this, we do not attach too much significance to a single measuring point. It was more the general tendency in which we were interested. The spreading of the measuring points

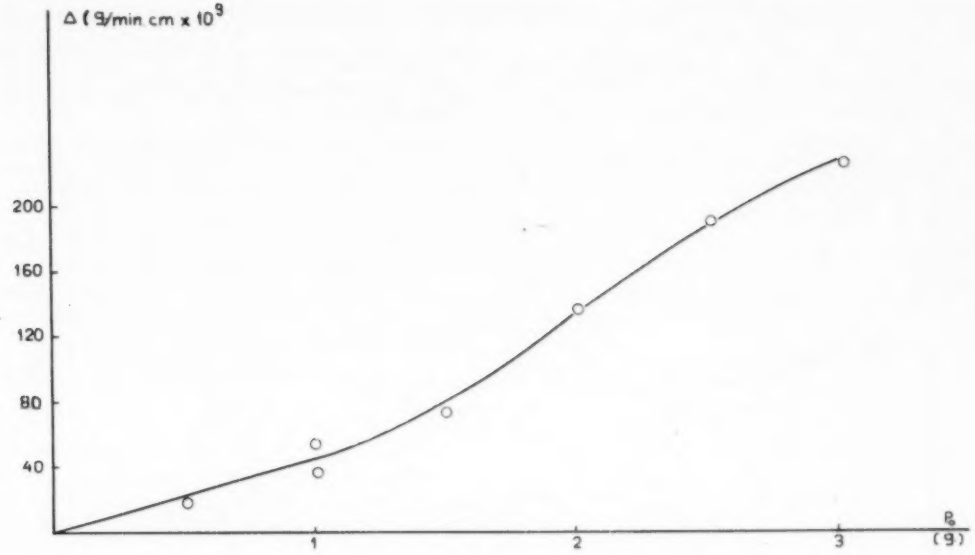

FIG. 11.

around this general tendency may be caused by the not entirely constant abrasive properties of the abrasive roller.

The results collected in Table I are given graphically in Figure 7. We see that in first approximation both the percentage loss in denier and the percentage loss in strength are functions of the time of abrasion, t, and these relationships can be represented by straight lines through the origins.

The measurement could not be continued to a decrease in denier further than about 20%, because in that case the ends of the worn-off part of the thread (q_1 and q_2 in Figure 6) had already worn away so far that the thread broke. Particularly with regard to the percentage loss in strength, it does not seem probable that this would continue to increase linearly with the time of abrasion at a larger decrease in denier than 20%. We will, however, assume that at least in the first approximation this is the case. This assumption enables the introduction of a new quantity—*viz.*, θ—which is the percentage loss in strength per percent loss in denier. This θ will be used for the interpretation of further measurements. θ is not a function of the time of wearing-off, t, owing to which it will be possible to formulate the wear phenomenon more clearly. It must, however, be borne in mind that our final formula will be an approximation again, although it will have to be appreciably better than formula (5), particularly for smaller losses in denier.

The subject of the following experiments was the determination of the percentage decrease in denier and strength at various times of wearing-off and at various loads, P_0.

In order to reduce the total measuring time, the number of determinations per measuring point was limited to 10. It was found that with this limited number of determinations per measuring point the decrease in denier was still progressing in a very definite way. The decrease in strength, for which a far greater spread was always observed, was, however, less definitely determined in this way. The results of the measurements are given in Figure 8. In these graphs the linear increase in the loss in strength with the time of wearing-off has been indicated by means of dash lines in order to point out that the data refer to estimates.

The filament under examination was a filament of 2.5 den., the normal production of the pilot plant.

From the graphs of Figure 8, θ, the percentage loss in strength per percent loss in denier, was now determined as a function of P_0 (see Figure 9). We

see that in the first approximation θ is also a linear function of P_0.

Moreover, with every measurement the friction coefficient, μ, was measured at a certain load P_0 by inserting a tensiometer between the rollers r_1 and r_2 of the measuring arrangement, as shown in Figure 6. When μ is known, it is possible to calculate the frictional energy per min. per cm. of thread length, A, which is spent on the thread surface at a load P_0.

Moreover, from the data of Figure 8 the quantity of material, Δ, in g. which is worn away per min. per cm. of thread length at a load P_0 can be calculated. Thus, the quotient $\frac{\Delta}{A}$ indicates the efficiency η_{P_0} of the wearing-off. In Figure 10 η is given as a function of P_0.

The quantity of material, Δ, in g. which is worn away per min. per cm. of thread length as a function of P_0 is given in Figure 11. We see that Δ is not a simple function of P_0.

The graphs of Figures 8, 9, 10, and 11 show exactly what happens during the wearing-off. If a formula is to be derived for the time of wearing-off

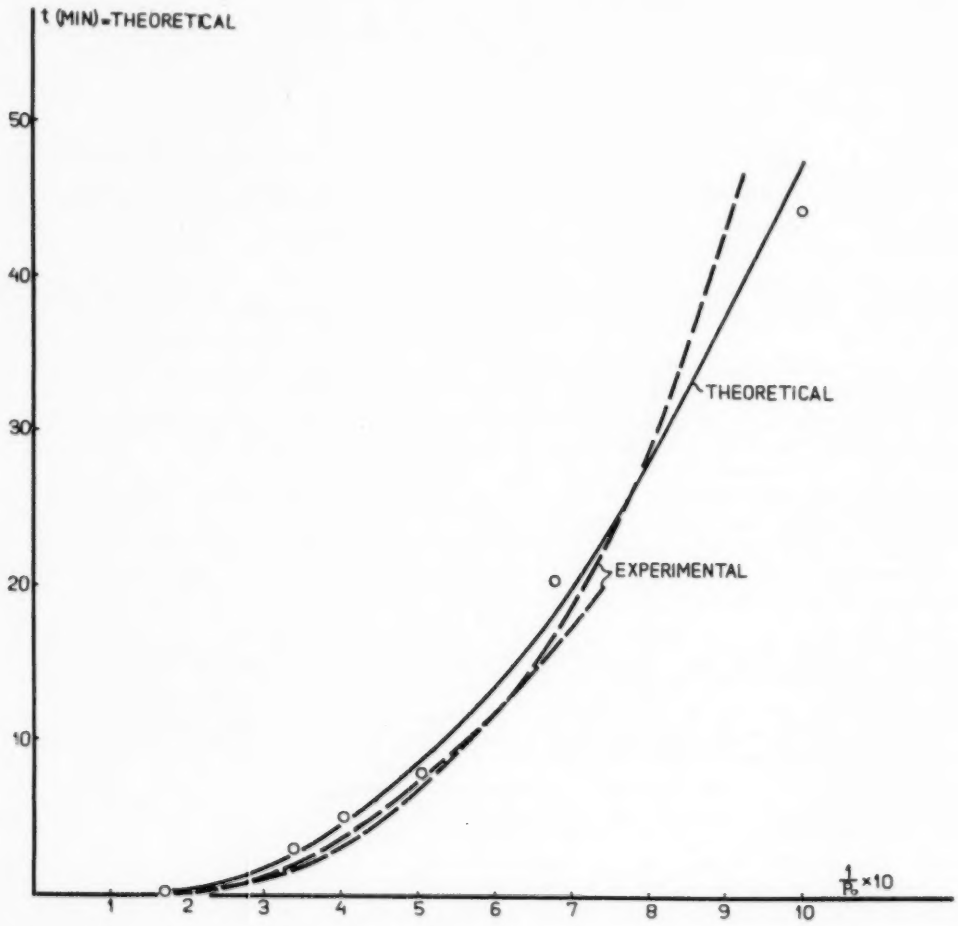

FIG. 12.

until break, t, then we must use the empirical data mentioned above.

Furthermore, it must be remembered that our second and third assumptions—viz., that η is independent of P_0 and that the strength of the thread during the wearing-off is constant—have been proven to be incorrect.

Assume the situation as given in Figure 6 to be such that the decrease in cross section of the thread per sec. at a load P_0 be σ cm.^{2}.

Thus, after a time of wearing-off of t sec. the cross section is $O - t\sigma$, where O = the initial cross section of the thread.

Expressed in terms of the initial cross section, the tension in the thread is then

$$\frac{O}{O - t\sigma} P_0.$$

Suppose further that the percentage decrease in strength per percent decrease in cross section (= decrease in denier) is α for a load P_0.

After t sec. the cross section has decreased by $\frac{t\sigma}{O} \times 100\%$.

The decrease in strength is then

$$\alpha \frac{t\sigma}{O} 100\%.$$

If the initial absolute strength of the thread is P_B, after t sec., the strength is

$$\frac{100 - \alpha \frac{t\sigma}{O} 100}{100} P_B = \left[1 - \alpha \frac{t\sigma}{O}\right] P_B.$$

The thread will break when the conditions of the following equation are fulfilled:

$$\frac{O}{O - t\sigma} P_0 = \left[1 - \alpha \frac{t\sigma}{O}\right] P_B. \qquad (6)$$

The time of abrasion until break, t, calculated from formula (6) becomes:

$$t = \tfrac{1}{2}\left(\frac{1}{\alpha}\frac{O}{\sigma} + \frac{O}{\sigma}\right) - \sqrt{\tfrac{1}{4}\left(\frac{1}{\alpha}\frac{O}{\sigma} + \frac{O}{\sigma}\right)^2 + \frac{O^2}{\sigma^2}\frac{1}{\alpha}\left(\frac{P_0}{P_B} - 1\right)}. \qquad (7)$$

In this formula, which must be considered a better approximation than formula (5), neither α nor σ is constant, but both quantities are dependent upon P_0. A better notation is:

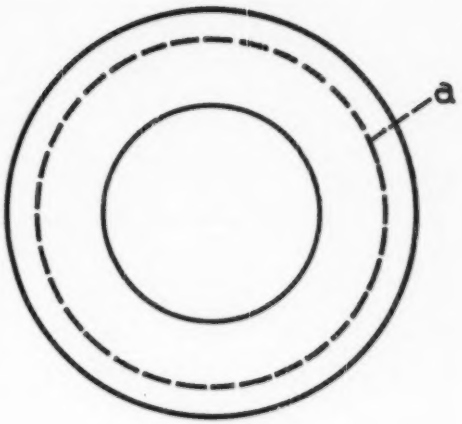

FIG. 13.

$$t = \tfrac{1}{2}\left(\frac{1}{\alpha_{(P_0)}}\frac{O}{\sigma_{(P_0)}} + \frac{O}{\sigma_{(P_0)}}\right) - \sqrt{\tfrac{1}{4}\left(\frac{1}{\alpha_{(P_0)}}\frac{O}{\sigma_{(P_0)}} + \frac{O}{\sigma_{(P_0)}}\right)^2 + \frac{O^2}{[\sigma_{(P_0)}]^2 \alpha_{(P_0)}}\left[\frac{P_0}{P_B} - 1\right]}. \qquad (8)$$

For the measurements described in Part II, formula (8) has been applied in order to indicate t as a function of $\frac{1}{P_0}$. The results are given in Figure 12.

Thus, for calculating the points in this graph, the empirically determined values $\alpha_{(P_0)}$ and $\sigma_{(P_0)}$ were used.

Although the determinations described in Part I were not carried out under exactly the same experimental conditions as those described in Part II, yet the variation of t as a function of $\frac{1}{P_0}$ must be about the same for both measurements on a similar experimental yarn.

As the measurements described in Part I had also been carried out on a yarn of 2.5 den., they are comparable with those of Part II.

In Figure 12 the measurements presented in Part I (Figure 2) have been indicated by a dash line; the scale was chosen so that the shapes of the curves could be compared as accurately as possible.

The similarity is fairly close, from which it may be concluded that formula (8) indeed describes the essence of exactly what happens during the abrasion process.

TABLE II

(FILAMENT OF 2.5 DEN.; $P_0 = 2.5$ G.)

Stretch (%)	Time of abrasion (min.)	Decrease in den./min. σ (%)	Decrease in strength/min. β (%)	Percentage decrease in strength per percent decrease in den. α (%)	Minute-strength (M. S.)	t_{15} (min.)	t_∞ (min.)	P_B (g.)
0	0.73	9.6	19.4	2.02	$0.73P_B$	1.0	0.28	3.4
10	1.10	4.9	8.2	1.68	$0.87P_B$	3.5	0.30	4.28
20	1.46	7.2	9.0	1.25	$0.84P_B$	3.25	0.40	4.7
30	1.46	4.9	13.5	2.76	$0.82P_B$	3.0	0.35	4.9
40	2.20	5.0	10.9	2.18	$0.85P_B$	3.4	0.36	4.7
50	2.20	4.0	10.8	2.70	$0.86P_B$	4.75	0.44	6.3
60	2.20	3.9	7.8	2.00	$0.88P_B$	6.75	0.47	7.3
70	2.20	1.0	9.8	9.80	$0.89P_B$	6.75	0.56	7.8
80	2.20	3.0	11.8	3.90	$0.86P_B$	6.75	0.51	8.6

As is evident from the above, during the longitudinal abrasion of a yarn there occurs not only loss in denier but also loss in strength.

What causes this loss in strength? An attempt can be made to explain this with the aid of the skin-core theory. The molecular orientation is far better in the skin than in the core; thus, the skin is stronger than the core. When the skin wears away (*e.g.*, to *a*: Figure 13), the absolute strength of the thread will be less than the calculated value for the absolute strength (calculated on the assumption that we are concerned with a homogeneous thread (without skin-core)).

This leads to loss in strength—that is, loss in relative strength, in g./100 den.

Although it is now possible, and even probable, that something like this takes place during the longitudinal abrasion, yet this view cannot explain all the phenomena, for in this case the loss in strength should be independent of P_0. It was observed, however, that the percentage loss in strength per percent loss in denier increases with increasing P_0 (see Figure 9).

As a working hypothesis, we will assume that the loss in strength is caused in the following way:

Imagine a homogeneous thread (without skin-core). When such a thread is subjected to longitudinal wearing-off, not only is the material of the thread worn away but the surface of the thread also becomes rough—that is, it cracks and fissures are formed. When the thread is now loaded with a weight (P_0), localization of high tension may occur in the strongly disturbed molecular regions on the thread surface at the cracks. These highly loaded regions soon cannot bear the maximum applicable loads at these places, and then cracks occur which initiate the breakage of the whole thread. Presumably, the breakage of the whole thread will occur immediately after a more or less important complex of molecules on the thread surface has been disrupted owing to the excessive loads at these places.

Now imagine that the increase in the percentage loss in strength per percent loss in denier with increase of P_0 is caused by the fact that the thread surface is roughened more appreciably with a larger P_0 than with a smaller P_0. With a small P_0 the thread is, so to speak, worn away "carefully"—that is, the thread surface is less rough. With a high P_0 the roughness of the thread is more pronounced, and the disorganization of the molecular regions on the thread surface is great, as a result of which the maximum permissible tensions at those places decrease appreciably.

A consequence of the above is that the percentage loss in strength per percent loss in denier will also have to be dependent upon the abrasive properties of the abrasive roller. At a constant load P_0 the loss in strength will vary, depending upon the "smoothness" of the abrasive roller—*i.e.*, the particle size of the diamond-bort.

Part III

Our investigation of the longitudinal abrasion of filaments was continued on a series of threads spun with various stretches. Viscose 7.6/6.7, 100/40 threads were stretched from 0% to 80%. As the various quantities to be determined are dependent on the load P_0, only one load P_0—*viz.*, 2.5 g.—was

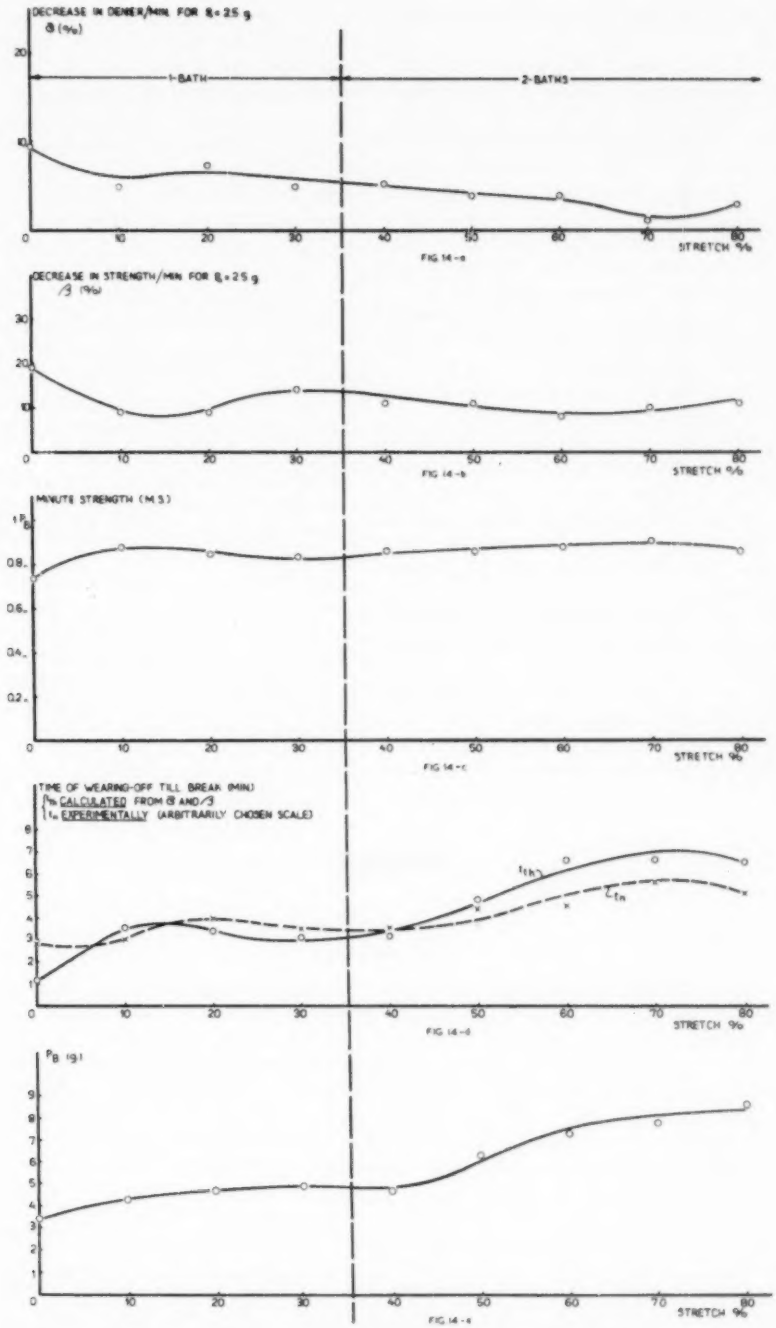
DECREASE IN DENIER/MIN FOR g = 2.5 g
α (%)
1-BATH
2-BATHS
STRETCH %
DECREASE IN STRENGTH/MIN FOR g = 2.5 g
β (%)
MINUTE STRENGTH (M.S.)
TIME OF WEARING-OFF TILL BREAK (MIN)
CALCULATED FROM α AND β
EXPERIMENTALLY (ARBITRARILY CHOSEN SCALE)
P_B (g)

FIG. 14a–e.

applied in order to enable comparison of the various experiments.

For every type of thread the decrease in den./min., $\bar{\sigma}$, and the decrease in strength/min., β, were determined at one time of wearing-off (see column 2 in Table II). Each value represents the average of 30 determinations. From these the percentage decrease in strength/percent decrease in denier, α, was calculated.

In order to keep the strength of the thread distinct from the wear susceptibility of the thread, we introduce the concept "minute-strength" (M. S.)—*i.e.*, the absolute strength of the thread after a 1-minute wearing-off, expressed in terms of the original absolute strength P_B.

Further, the theoretical time of wearing-off, t_{th}, was calculated with the aid of formula (8).

The time of wearing-off until break, t_n, was also determined by continuing the abrasion process in the normal way until the threads broke—*i.e.*, the filament rested motionless on the rotating abrasive roller. In this case, our considerations in Part II apply as well. The variation of t_{th} as a function of the stretch must occur in about the same way as that of t_n as a function of the stretch if formula (8) really describes what essentially happens during the wearing-off process.

The results of this investigation have been collected in Table II and in Figure 14*a–e*.

When considering the results (see Figure 14*a–d*), it is striking that the minute-strength, M. S., as a function of the stretch (Figure 14*c*) changes very little with increasing stretch. The result is that with these experimental threads the wear susceptibility does decrease with increasing stretch, but the decrease cannot be called important. However, two favorable stretches can be mentioned—*viz.*, 1-bath, 10% to 20% of stretch, and 2-bath, about 70% of stretch.

In Figure 14*d* the theoretical time of wearing-off until break has been plotted against the percent stretch. The two stretches mentioned above are clearly visible in this graph.

Moreover, the graph shows a decided difference in the case of increasing stretch. With this measurement the latter difference is not affected because $\bar{\sigma}$ and α become far more favorable with increasing stretch, but because the absolute strength P_B improves appreciably (Figure 14*e*).

So, with this measurement the absolute strength is the important quantity, by which the difference in resistance to abrasion between the various threads is mainly caused.

In Figure 14*d*, t_n has been plotted against the percent stretch. The scale value for t_n was again chosen so that the shape of both curves could be compared as accurately as possible. We see that the general shape of t_{th} corresponds with that of t_n. This indicates again the qualitative serviceability of formula (8).

[*Manuscript received August 4, 1949.*]

Correction

In "Cellulose Studies, XIII, XIV, XV," by Richard Steele and Eugene Pacsu, which appeared in TEXTILE RESEARCH JOURNAL, December, 1949, through an unfortunate oversight, two errors of omission were made. Dr. Steele was an Avondale Mills Fellow of the Textile Research Institute while engaged in the work reported in this paper. The authors wish to acknowledge the Avondale Mills, Sylacauga, Alabama, whose financial support of Dr. Steele's Fellowship made possible his participation in this study. They are also indebted to the Office of Naval Research, under Contract No. N7-onr-374, Task Order I, Amendment 1, for the Perkin-Elmer recording infrared spectrometer which was used in this work.

Submicroscopic Structure of Cellulose from Nitrogen-Sorption Measurements*

Charles M. Hunt, Raymond L. Blaine, and John W. Rowen

National Bureau of Standards, Washington, D. C.

Abstract

When cotton linters were soaked in cold 10% sodium hydroxide, washed and neutralized, transferred successively to methyl alcohol and benzene, and carefully dried at reduced pressure, a surface area as great as 71.3 sq. m. per g. was obtained by the Brunauer-Emmett-Teller technique. Previously obtained areas for untreated cotton were all less than 1 sq. m. per g. Linters carried through the above steps after soaking in water instead of in alkali had areas as great as 47.3 sq. m. per g. When the alkali-treated sample was conditioned in water vapor to a 3.3% gain in weight, the surface decreased to 31.6 sq. m. per g.; further conditioning to an 11.0% gain in weight decreased the surface to 2.1 sq. m. per g.

The isotherms of the treated samples showed strong hysteresis, while the isotherms of untreated cotton showed little or no hysteresis.

Calculations of pore-size distribution by the method of Wheeler and Shull indicated that these materials have rather narrow distribution ranges, the alkali-treated material having a maximum at a pore radius of about 20 Å. and the water-soaked material a maximum at about 16 Å.

I. Introduction

The view that native and regenerated cellulose fibers contain longitudinal submicroscopic channels or that such a structure can be produced by imbibition of water has been suggested from a number of lines of evidence—for example, x-ray and ultramicroscopic studies of fibers in which metals have been deposited from solution [8, 9, 14]. A review of this subject has been presented by Frey-Wyssling [10] and Hock and Mark [15*a*]. The existence of channels in wet cellophane has been suggested to explain its use as a semipermeable membrane, and Valko [15*b*] has reviewed the measurement of pore diameters in this material by different methods and has cited values, most of which lie between 40 and 60 Å. The observation of Collins [5, 6] that cotton and rayon fibers swell laterally but very little longitudinally upon imbibing of water indicates that some sort of lateral separation of the chains occurs in the swelling process.

Previous work in this laboratory showed that the surface area of a cotton sample was 0.72 sq. m. per g. when based on the sorption of nitrogen at liquid-nitrogen temperatures and calculated by the Brunauer-Emmett-Teller equation. When this equation was applied to the data based on the sorption of water at 25°C by the same cotton, a specific surface of 108 sq. m. per g. was obtained. From this it was evident that water had access to regions within the fiber which were unavailable to nitrogen. Shaw and coworkers made a similar observation when they compared the water and nitrogen absorption of certain proteins [18] and sodium pectate [16]. However, Assaf, Haas, and Purves [1, 2] reported that cotton linters soaked in sodium hydroxide and carried through a solvent-exchange procedure had a calculated area as great as 64.7 sq. m. per g. available to nitrogen. Thus, it appears that regions within the fiber ordinarily available only to water were made available to nitrogen.

The experiments reported here were undertaken in order to study the structure of expanded cellulose by low-temperature nitrogen sorption, because measurements of this type on other adsorbents have been found to have real significance. Cotton linters were carried through the procedure of Assaf, Haas, and Purves, and nitrogen adsorption-desorption isotherms were obtained. Pore-size distributions were calculated from the desorption data, as has been done for certain silica gels [19, 20] and other materials [3*c*]. The effect of adding water vapor to the expanded material was observed, and an experiment was carried out to see whether or not high nitrogen sorption

* This paper appeared also in the *Journal of Research of the National Bureau of Standards* for December, 1949.

could be obtained with cotton linters presoaked with water instead of with alkali.

II. Experimental Procedure

The sample of cotton linters used in this work was furnished by the Hercules Powder Company through the courtesy of H. M. Spurlin and Peter Van Wyck. It was designated a 05843 Grade 27LV Cotton Seed Hull Shavings Pulp. According to descriptive material furnished by the company, chemical cotton of this type is digested with dilute alkali and bleached. The sample had a reported * viscosity of 608 sec. in 2.5 g./100 ml. concentration in A.C.S. cuprammonium solvent, corresponding to an intrinsic viscosity of about 9 and a degree of polymerization of about 1,800. The material was used without further purification. The methyl alcohol and benzene used in the solvent-exchange described in this study were dried by distillation from sodium.

The control sample of cotton linters (sample *A*) received no treatment. Sample *B* was put through the procedure described by Assaf, Haas, and Purves [1] and neutralized after most of the alkali was removed. No preliminary dewaxing was performed because the material wet readily with water. After drying in vacuum the sample was stored several weeks over a drying agent and paraffin before use. The paraffin was used as an absorbent for desorbed benzene vapor. Sample *C* was prepared by soaking 5 g. of cotton linters for 3 hrs. in water at room temperature. The sample was then pressed to remove excess water and transferred to ¾ l. of absolute methyl alcohol. After 30 min. the sample was pressed and transferred to a second portion of methanol. The process was repeated once more with methyl alcohol and twice with benzene. The sample was vacuum-dried by intermittent evacuation to a pressure of about 25 mm. Hg and was stored over a drying agent and paraffin. This procedure is similar to that of Assaf, Haas, and Purves, but the preliminary swelling was done with water alone at room temperature instead of with 10% sodium hydroxide in an ice bath.

Five to 7 g. of samples *A*, *B*, and *C* were quickly transferred from the desiccator and sealed into glass holders. A glass plug was placed on top of each sample and this permitted the sealing flame to be applied 2 to 3 in. from the cotton without unduly increasing dead space. The tips of the holders were drawn out so that they could be easily broken off and resealed. Samples *A* and *C* were outgassed overnight, or longer if necessary, at room temperature in order to obtain a vacuum of 10^{-6} mm. Hg, and nitrogen adsorption-desorption isotherms were obtained. Nitrogen adsorption-desorption measurements were made on sample *B* both after outgassing at liquid-nitrogen temperature (determinations 1, 2, and 3) and after outgassing at room temperature (determination 4) in order to see if large differences would be obtained. Sample *B* was then conditioned at 20–25% relative humidity. Conditioning was accomplished by passing nitrogen through sulfuric acid of proper concentration, glass wool, and finally through the sample. Passage through the sample was achieved by breaking the tip of the holder; after constant weight was attained the tip was resealed. The sample was outgassed under liquid nitrogen in order to retain the water which had been added, and nitrogen adsorption-desorption measurements were made (determinations 5 and 6). The process was repeated after conditioning the sample at 70–75% relative humidity (determinations 7 and 8). The sample was then dried by passing nitrogen dried with magnesium perchlorate through the sample. Nitrogen adsorption-desorption measurements were made after outgassing at room temperature. This provided a means of determining whether any of the nitrogen-sorption capacity of the sample lost by hydration could be regained by removal of the water (determinations 9 and 10).

Nitrogen-adsorption measurements were made with an apparatus similar to that described by Emmett [7]. The saturation vapor pressure of the nitrogen at the temperature of the liquid-nitrogen bath was determined by a vapor-pressure thermometer, using the purified nitrogen employed for the adsorption experiment. A correction for the non-ideality of nitrogen was calculated, assuming that the volume of nitrogen in the dead space at 760 mm. Hg pressure was 5% greater than that calculated from the ideal gas laws, and that the percent deviation varied linearly with pressure, being negligible at very low partial pressures.

Pressure-volume measurements covering a range of p/p_o from less than 0.1 to above 0.9 were made, where p is the pressure of nitrogen above the sample and p_o is the vapor pressure of liquid nitrogen at the same temperature. Each adsorption-desorption isotherm determination required 2 or 3 days to complete. Apparently, longer times were required to reach equi-

* Private communication from Peter Van Wyck.

librium on the steeper portions of the curves than on the flatter portions. Final readings were recorded when two pressure readings taken 10 min. apart did not differ by more than 0.1 mm. Hg. Pressure readings obtained in this way usually agreed within 1 or 2% with readings obtained when the sample was left overnight, the drift being in the direction of slightly greater nitrogen adsorption in adsorption measurements and slightly less nitrogen adsorption in desorption measurements.

III. Nitrogen-Sorption Isotherms

The volumes (ml.) of nitrogen adsorbed per g. of sample are given in Table I, and typical isotherms are shown in Figures 1 and 2. The untreated cotton linters (Figure 2, curve A) adsorbed much less nitrogen than the other samples and had a type II isotherm [3*a*]; that is, the curve gave no indication of leveling off up to the highest partial pressure measured. No hysteresis was observed within the limits of experimental error. The adsorption of nitrogen by untreated cotton is conceived as being a multilayer adsorption process in which capillary condensation plays little or no part.

The cotton swollen with alkali and subjected to solvent-exchange (Figure 1, curve B) and the cotton swollen with water and subjected to solvent-exchange (Figure 2, curve C) had what appeared to be type IV isotherms [3*a*]. Strong hysteresis was observed, with inflection points in the desorption curves at partial pressures of 0.49 and 0.47, respectively.

When sample *B* was conditioned to a 3.3% gain in weight at a relative humidity of 20–25%, the isotherm (Figure 1, curve B') also appeared to be type IV, with strong hysteresis. The sorption capacity was smaller, however. When sample *B* was further conditioned at 70–75% relative humidity to a weight 11.0% greater than the weight of the original sample, the form of the isotherm changed completely (Figure 1, curve B''). It was more like a type II curve up to the highest partial pressure measured, and showed measurable hysteresis, with both branches convex in shape with respect to the pressure axis.

When sample *B* was redried after conditioning at 70–75% relative humidity, an isotherm identical with curve B'' in Figure 1 was obtained.

IV. Surface Areas

The volume of nitrogen required to cover the adsorbate with a unimolecular layer was determined from nitrogen-adsorption data between p/p_o values of 0.05 and 0.3 by methods already described [3*b*, 4, 7]. Surface areas were calculated from this volume, assuming that each nitrogen molecule covers an area of 16.2 sq. Å. The values are summarized in Table II. Each value in the table represents a single determination; the values are listed in the order in which the determinations were made.

The area of 0.5–0.6 sq. m. per g. for untreated cotton linters is comparable with the 0.72 sq. m. per g. previously obtained in this laboratory for a cotton yarn [17]. This is slightly larger than the value of 0.16 sq. m. per g. reported by Howell and Jackson [12] from microscopic measurements. This suggests that there may be a few accessible surface irregularities and pores, but nitrogen does not penetrate the untreated cotton fiber to any great extent.

However, when the linters were given the treatment of Assaf, Haas, and Purves, a large surface was obtained, such as they reported. Successive additions of water to the sample greatly decreased the surface available to nitrogen, and when the water was removed the surface area remained at the same low value. The sensitivity of surface area to small amounts of water indicates that refinements aimed at the complete removal and rigorous exclusion of water would lead to higher surface areas than those given in Table I.

The collapse of expanded cellulose upon wetting and drying suggests that the expanded material is in an unstable state. Recent unpublished work of P. H. Hermans * indicates that the expanded cellulose has an x-ray diffraction pattern which is somewhat different from that of native cellulose (cellulose I). Since expanded cellulose tends to revert to cellulose I upon wetting, it appears that the water molecules assist the cellulose in the expanded state in getting over a special energy barrier. Water probably facilitates lateral and transverse ordering through the formation of hydrogen bonds. It is believed that this ability of the cellulose molecule to become linked with other cellulose molecules by means of intermolecular hydrogen bonding is responsible for many of the physical properties of cellulose, such as insolubility and strength.

Swelling with water followed by solvent-exchange from methyl alcohol to benzene without prior alkali treatment also produced a large increase in the calculated surface area of the cotton linters. Thus, while 10% sodium hydroxide undoubtedly produced struc-

* Communication through Dr. Mark to one of the authors.

TABLE I. NITROGEN SORBED BY COTTON LINTERS

Sample A—Control				Sample B																Sample C			
Detn. 1*		Detn. 2		Detn. 1		Detn. 2		Detn. 3		Detn. 4†		Detn. 5‡		Detn. 6		Detn. 7		Detn. 8§		Detn. 9		Detn. 10		Detn. 1		Detn. 2**	
p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption	p/p_o	ml. N_2 per g. Adsorption
0.081	0.14	0.075	0.11	0.006	7.0	0.090	14.2	0.024	10.5	0.018	10.3	0.079	6.4	0.096	6.7	0.113	0.52	0.107	0.48	0.114	0.51	0.128	0.52	0.027	7.8	0.055	8.8
0.152	0.15	0.138	0.13	0.029	11.6	0.131	15.7	0.031	11.1	0.090	14.7	0.126	7.1	0.125	7.1	0.154	0.56	0.146	0.53	0.156	0.54	0.155	0.55	0.037	7.7	0.084	9.7
0.194	0.17	0.185	0.13	0.038	12.3	0.251	19.5	0.126	15.1	0.131	16.2	0.196	8.1	0.155	7.5	0.202	0.60	0.191	0.54	0.204	0.56	0.182	0.55	0.120	10.3	0.159	11.5
0.249	0.19	0.228	0.13	0.076	14.2	0.287	20.8	0.149	16.1	0.203	18.6	0.245	8.9	0.213	8.4	0.257	0.63	0.261	0.62	0.267	0.61	0.227	0.60	0.192	12.0	0.207	12.5
0.283	0.19	0.280	0.14	0.109	15.5	0.362	23.6	0.177	16.9	0.250	20.2	0.302	9.8	0.261	9.1	0.312	0.65	0.355	0.64	0.363	0.64	0.250	0.61	0.269	13.8	0.256	13.6
0.360	0.19	0.346	0.11	0.144	17.3	0.436	26.8	0.239	18.9	0.294	21.8	0.419	12.0					0.463	0.72	0.471	0.72			0.316	14.9	0.333	15.4
0.516	0.17	0.430	0.19	0.178	17.9	0.519	31.0	0.274	20.2	0.389	25.6	0.616	18.1					0.562	0.79	0.596	0.84					0.525	20.0
0.692	0.25	0.568	0.17	0.209	19.0	0.589	35.6	0.347	22.8	0.387	25.9	0.718	23.0					0.678	0.97	0.747	1.23					0.654	22.8
0.813	0.41	0.672	0.19	0.240	20.0	0.641	39.2	0.422	25.9	0.531	33.3	0.716	23.1					0.832	1.90	0.855	2.16					0.806	25.4
0.928	0.66	0.789	0.22	0.274	21.3	0.702	45.5	0.506	30.2	0.611	38.8	0.826	28.5					0.923	3.83	0.942	4.31					0.786	25.8
		0.931	0.47	0.320	23.0	0.827	53.6	0.573	34.5	0.701	46.4	0.959	34.0													0.872	27.1
Desorption						0.878	55.9	0.636	39.5	0.783	53.0							Desorption		Desorption						0.958	30.0
		Desorption				0.987	61.1	0.632	39.8	0.844	56.2	Desorption															
0.813	0.38							0.715	46.6	0.954	61.0															Desorption	
0.709	0.30	0.732	0.20			Desorption		0.819	54.0	0.974	62.3							0.819	2.59	0.843	2.90						
0.515	0.21	0.607	0.18					0.833	54.5			0.842	31.2					0.813	2.54	0.847	2.92					0.862	27.6
0.327	0.18	0.468	0.14			0.804	56.0	0.942	59.3	Desorption		0.665	27.6					0.667	1.38	0.715	1.68					0.613	25.1
0.266	0.17	0.381	0.18			0.686	53.4	0.976	61.3			0.531	25.0					0.555	0.96	0.598	1.05					0.515	24.3
		0.313	0.17			0.554	50.3			0.823	58.0	0.478	17.6					0.469	0.74							0.475	22.4
		0.271	0.18			0.495	42.9	Desorption		0.665	54.3	0.340	10.5					0.413	0.68							0.455	20.3
		0.239	0.20			0.442	28.0			0.527	51.0							0.304	0.65							0.291	15.1
		0.195	0.16			0.308	22.1	0.812	56.7	0.494	44.2							0.163	0.57								
						0.277	21.0	0.789	56.1	0.493	44.0																
						0.206	18.6	0.656	53.1	0.475	34.3																
						0.156	17.0	0.522	49.9	0.363	25.2																
						0.136	16.4	0.508	49.5	0.245	20.9																
								0.491	46.5	0.163	18.1																
								0.496	46.1	0.109	16.3																
								0.475	33.3	0.074	15.0																
								0.434	28.1																		
								0.360	24.6																		
								0.243	20.4																		
								0.161	17.7																		
								0.107	16.0																		
								0.072	14.7																		
								0.050	13.7																		

* Plotted in Figure 2 as curve A.
† Plotted in Figure 1 as curve B.
‡ Plotted in Figure 1 as curve B'.
§ Plotted in Figure 1 as curve B".
** Plotted in Figure 2 as curve C.

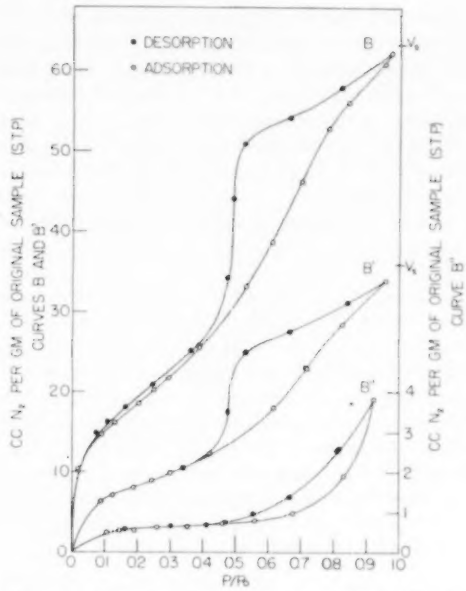

FIG. 1. *Nitrogen adsorption-desorption isotherms (Sample B). B—Alkali-swelled, solvent-exchanged cotton linters (determination 4). B'—B conditioned at 20–25% relative humidity (determination 5). B"—B' conditioned at 70–75% relative humidity (determination 8).*

tural changes in the cotton fiber, the use of alkali was not necessary to make comparatively large regions within the fiber available to nitrogen. A paper by Kistler is of interest in this connection [13]. He prepared aerogels from a large number of inorganic and organic materials by substituting a swelling liquid within the gel by using a liquid which could be evaporated above its critical temperature in an autoclave. Thus, it was possible to replace the liquid in the structure with a gas without allowing the surface of the liquid to "recede within the gel." Kistler states that this last condition is quite important. He prepared an aerogel from cellophane by extracting the wet material with ether, followed by propane. The propane was removed in an autoclave at 115°C.

The procedure employed here differed in at least one important respect from that of Kistler in that the final liquid used was benzene, which was removed at room temperature. However, the high sorption capacity for nitrogen suggests that the material had some of the properties of an aerogel. Apparently, the cotton linters possessed sufficient rigidity to retain

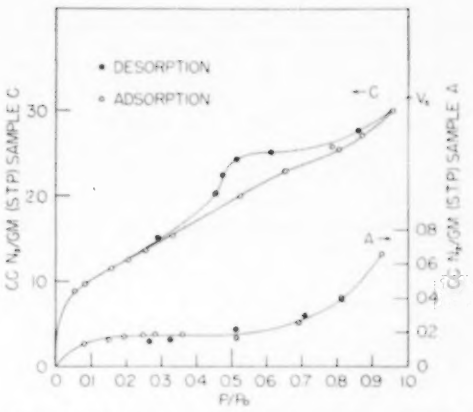

FIG. 2. *Nitrogen adsorption-desorption isotherms (Samples A and C). A—Control cotton linters (determination 1). C—Water-swelled, solvent-exchanged cotton linters (determination 2).*

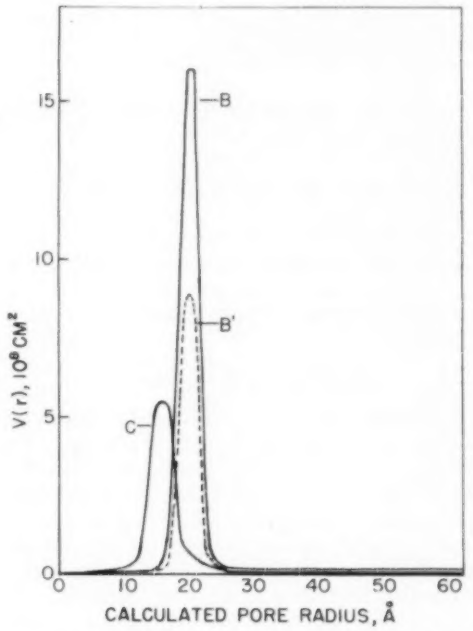

FIG. 3. *Pore-size distribution curves (Samples B and C). B—Alkali-swelled, solvent-exchanged cotton linters (determination 4). B'—B conditioned at 20–25% relative humidity (determination 5). C—Water-swelled, solvent-exchanged cotton linters (determination 2).*

TABLE II. SUMMARY OF SURFACE-AREA DETERMINATIONS

	Determination No.	Specific surface (sq. m. per g. of sample)
Sample A, control	1	0.6
Outgassed at room temperature	2	0.5
Sample B, NaOH and solvent-exchange	1	71.3
Outgassed at liquid-nitrogen temperature	2	68.2
	3	67.7
Outgassed at room temperature	4	70.4
Sample B, conditioned at 20–25% R.H.	5	31.6
Outgassed at liquid-nitrogen temperature	6	30.8
Sample B, conditioned at 70–75% R.H.	7	2.1
Outgassed at liquid-nitrogen temperature	8	2.0
Sample B, redried	9	2.0
Outgassed at room temperature	10	2.1
Sample C, solvent-exchange only	1	47.3
Outgassed at room temperature	2	46.5

much of the expanded structure even though the benzene-air interface was allowed to "recede within the gel." As already noted [2], water cannot be removed in this way without collapsing the expanded structure of cellulose.

It is to be noted in Table II that a repeated surface-area measurement on the expanded material is usually slightly lower than the preceding measurement. This again suggests that the expanded state is unstable.

V. Pore-Size Distributions

Hysteresis in the sorption isotherms of samples *B* and *C* has suggested that capillary condensation plays a part in the process. Although it is possible to interpret hysteresis on the basis of other factors than capillary condensation, and although modern statistical mechanical treatments of sorption do not explicitly interpret it in terms of capillary condensation [11], hysteresis in the isotherms of rigid solids has generally been attributed to this mechanism. Brunauer [3c] has reviewed much of the work on this subject. Postulation of the existence of channels in wet cellulose based on evidence previously mentioned suggested that pores might exist in cellulose from which water had been removed by solvent-exchange.

Pore-size distributions have been calculated by the method of Wheeler [21] and Shull [19] from the desorption isotherms plotted in Figure 1, curves B and B′, and Figure 2, curve C. These distributions have been plotted in Figure 3.

The method is briefly outlined here. It corrects the capillary radii, as calculated by the Kelvin equation, for the thickness of the layer of gas laid down by multilayer adsorption. The pore-size distribution is based upon integration of the equation:

$$V_s - V = \pi \int_R^r (r - t)^2 L(r) dr, \qquad (1)$$

where V_s is the volume of gas adsorbed at saturation pressure, V is the volume of gas adsorbed at any given partial pressure, r is the pore radius, t is the thickness of gas laid down by multilayer adsorption, $L(r)dr$ is proportional to the total length of pores whose radii fall between r and $r + dr$, and R is the Kelvin radius corrected for multilayer adsorption and is given by the expression:

$$R = t - \frac{2\sigma v}{R_g T \ln p/p_o}, \qquad (2)$$

in which σ is the surface energy of the adsorbate at the temperature of adsorption T, v is the molar volume of the adsorbate in the liquid state, R_g is the gas constant in ergs/mole/degree, and p/p_o is the relative pressure.

Equation (1) is integrated by assuming that $L(r)$ is either a Maxwellian distribution,

$$L(r) = A_o r_o C^{-r/r_o}, \qquad (3a)$$

or a Gaussian distribution,

$$L(r) = A_1 C^{-(B_1(r_1)(r-r_1)^2}, \qquad (3b)$$

or the sum of a Maxwellian and a Gaussian distribution,

$$L(r) = A_o r_o C^{-r/r_o} + A_1 C^{-(B_1(r_1)(r-r_1)^2}. \qquad (3c)$$

A_o and A_1 are constants, and r_o, r_1, and B_1 are parameters.

By way of illustration, when the equation for a Maxwellian distribution (equation (3a)) is substituted in equation (1) and the integration is carried out, the expression

$$V_s - V = A_o r_o^4 M(R, r_o) \qquad (4)$$

is obtained, where $M(R, r_o)$ is a function of R, r_o and contains t, the multilayer thickness. Shull has calculated this function for a number of values of R and r_o and has prepared a family of standard inverted isotherms by plotting $M(R, r_o)$ against R on the logarithmic scale of semilog paper. Experimental $V_s - V$ values are similarly plotted on a logarithmic scale against R, and the curve is matched with the standard isotherms to find the one giving the closest fit. This gives the parameters of the standard distribution most closely approximating the experimental distribution, and the constant A_o may be obtained by substituting values of r_o, $M(R, r_o)$, and $V_s - V$ in equation (4). The procedure is similar for a Gaussian distribution and entails a few more steps for the sum of a Maxwellian and a Gaussian distribution, but involves curve-matching in each case. The total volume of gas sorbed in pores with radii between r and $r + dr$ is $V(r)dr$, and this volume distribution function is given by

$$V(r) = \pi r^2 L(r). \qquad (5)$$

Certain assumptions have been made in applying this method. The first is the basic assumption of the method itself, that the sorption process takes place in circular pores whose radii may be calculated from the Kelvin equation, corrected for multilayer adsorption. It has also been assumed that V_s, the volume of nitrogen required to condense and exactly fill the pores, may be obtained by extrapolating the isotherm to saturation pressure, and it has been assumed that the adsorbent undergoes no important dimensional changes during sorption.

Sample B (Figure 3, curve B) is shown as having most of the nitrogen sorbed within a rather narrow distribution range of pore radii, with a maximum volume at a pore radius of 20 A. When the sample was conditioned at 20–25% relative humidity (Figure 3, curve B'), the maximum volume remained at about the same pore radius. The mechanism by which addition of water to expanded cotton reduces subsequent capacity for nitrogen is not clear at present. It is difficult to visualize a uniform multilayer process by which water could be deposited in pores without decreasing pore radius. If it is assumed that a certain fraction of the entire pore length in the sample is completely destroyed by water while the remainder is left intact, pore volume could be decreased without changing pore radius. The volume of water added was nearly large enough to account for the decreased pore volume if it had merely taken up space and had exerted no specific action in the collapse of the structure; 11% of water was more than enough to account for the pore volume of the original sample on this basis, which suggests that additional swelling of the expanded cotton had taken place upon conditioning at 70–75% relative humidity.

When the desorption measurements on solvent-exchanged cotton (Figure 3, curve C) were analyzed by the Wheeler-Shull method, a slightly broader distribution of pore radii, with a maximum at 16 A., was obtained.

No curves are shown for the control sample or the cotton conditioned at 70–75% relative humidity because of the difficulty in estimating V_s for a type II curve. For a true multilayer adsorption process on a plane surface, V_s should approach infinity and a pore-volume calculation would have no physical significance.

VI. Summary

A sample of cotton linters swollen with strong alkali and given a solvent-exchange treatment was found to have a large surface area available to nitrogen. This confirms the observation of Assaf, Haas, and Purves. The shapes of the adsorption and desorption isotherms were found to be more like type IV than type II isotherms, and they showed strong hysteresis. Pore-size distributions, calculated by the method of Wheeler and Shull, showed that most of the nitrogen was absorbed in pores having radii of about 20 A.

Addition of about 3.3% moisture to the expanded cotton reduced the surface area greatly without noticeably changing the type of isotherm or the pore radius. Addition of about 11.0% moisture destroyed nearly all of the internal surface, and the isotherm more closely resembled that of untreated cotton but a slight hysteresis remained.

Cotton swollen with water only and given solvent-exchange also had a much larger surface than untreated cotton. The isotherm was more nearly a type IV, and most of the nitrogen was adsorbed in pores having calculated radii of about 16 A.

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New Abstracts Service

Subscribers to TEXTILE RESEARCH JOURNAL are reminded that the Abstracts Section of the JOURNAL has been discontinued, and that they will receive monthly, beginning January, 1950, the Abstracts Section of the *Journal of the Textile Institute* of England, printed as a separate publication and mailed from England direct to each subscriber. All types of subscriptions to TEXTILE RESEARCH JOURNAL include the British Abstracts publication.

T.R.J. Index for 1949

The Index to TEXTILE RESEARCH JOURNAL, Volume 19, 1949, will be printed as a separate publication and mailed to the subscribers to that volume either late in February or early in March.

Letters to the Editor

Prevention of Supercontraction in Modified Wool Fibers

HARRIS RESEARCH LABORATORIES
1246 Taylor Street, N.W.
Washington 11, D. C.

October 4, 1949

To the Editor
TEXTILE RESEARCH JOURNAL

Dear Sir:

Although setting reactions have long ago achieved commercial importance both in the woolen and hair-waving industries, it is only since the early thirties that the problem has received scientific investigation [2, 7]. "Set" is the term used here to describe the general phenomenon whereby a keratin fiber maintains a length greater than its original length as a result of a given treatment. It is also possible for a fiber to be fixed at a length less than its original length, and such set is referred to as "supercontraction."

On the basis of extended investigations, Speakman [8] suggested that supercontraction is mainly associated with fission of the disulfide linkages. He showed that under certain conditions compounds such as sodium sulfide, sodium bisulfite, silver sulfate, and potassium cyanide—a variety of agents which rupture disulfide bonds—supercontract wool or hair fibers. In recent years, both supercontraction and set have been the subject of a great deal of investigation because of their importance in the understanding of keratin reactivity and structure. As a result of much of this work it is now generally recognized that the rupture of covalent disulfide bonds, and of secondary forces such as electrostatic salt linkages and probably hydrogen bonds, occurs during supercontraction reactions [1, 3, 5].

The supercontraction which occurs when keratin fibers are treated with boiling sodium bisulfite solutions has perhaps been studied in the greatest detail, and it is definitely established that the type of keratin fiber, as well as its previous history, affects the magnitude of supercontraction [12]. Supercontraction behavior may therefore be used as a means for detecting changes in the condition of a fiber. Moreover, since supercontraction is associated with breakdown of cross-linkages, lack of supercontraction would be considered evidence for the presence of stabilized cross-linkages in the keratin network. It has been shown that treatment of wool with alkali [9], with the formation of stable —C—S—C— bonds, eliminates supercontraction in boiling bisulfite. It is also known that certain formaldehyde treatments which may introduce additional stabilizing cross-linkages in the keratin molecule yield modified fibers which do not supercontract in bisulfite [11].

Some years ago, we described the modification of wool fibers by reduction with thioglycolate and subsequent alkylation with alkylene dihalides [6]. It could be predicted from the above that the conversion of the disulfide groups to *bis*-thioethers by this reaction would affect the supercontraction behavior, and it was shown that such modified fibers indeed did not supercontract in bisulfite [10]. More recently, we have described the preparation of modified stabilized wool by simple, inexpensive one-step modification treatments involving simultaneous reduction and alkylation with inorganic reducing agents, such as sulfoxylates and hydrosulfites, and alkylene dihalides at elevated temperatures [4]. Chemical evidence, and the determination of mechanical properties, indicated the presence of stabilized cross-linkages through modification of disulfide groups [4]. The supercontraction behavior of such modified wools has now been determined.

The data for wool modified with hydrosulfite and ethylene dibromide are given in Table I. The values given are the averages for 10 fibers. The treated and untreated fibers were boiled simultaneously in the respective solutions so that all were treated identically. The modified fibers supercontracted less than 1% in bisulfite, whereas the untreated fibers supercontracted almost 20%. Similar experiments were performed with fibers modified with sodium sulfoxylate formaldehyde, and methylene dibromide as previously described [4], and again the treated fibers supercontracted less than 1% in bisulfite, whereas the untreated fibers supercontracted 26%.

In the study of the modification reactions, it was found that wool was severely damaged and fibers

TABLE I. SUPERCONTRACTION BEHAVIOR OF UNTREATED AND MODIFIED WOOL FIBERS

Treatment	Supercontraction* in 5% $NaHSO_3$ (%)	Supercontraction† in 0.2% $Na_2S_2O_4$ (%)
Untreated	19.2	25.6
$Na_2S_2O_4$-$(CH_2)_2Br_2$‡	0.7	0.7

* Fibers were treated for 30 min. at the boil.

† The bath was adjusted to pH 8.3 with 0.25*M* borate. Treatment was for 30 min. at the boil.

‡ The fibers were treated along with a piece of wool cloth in a bath containing 0.5% borax (in solution) and 5% sodium hydrosulfite and 10% ethylene dibromide on the weight of the wool. The bath ratio was 30:1, the pH was 9.0, and the treatment was carried out for 30 min. at 95°C.

supercontracted if alkylene dihalide was omitted from the reaction bath containing hydrosulfite at elevated temperature. Thus, alkaline hydrosulfite is also an excellent supercontraction medium. It is seen in Table I that the modified fibers did not supercontract in this medium, whereas the untreated fibers supercontracted 25%.

This behavior on omission of alkylene dihalide from a hydrosulfite bath suggested an interesting experiment—that is, the addition of alkylene dihalide to bisulfite baths to prevent supercontraction. The reaction was carried out in baths adjusted to pH 8.2 with 0.25*M* borate buffer so that rapid alkylation could occur. The data in Table II show that the addition of ethylene dibromide indeed prevented supercontraction. To our knowledge, this is the only recorded example of the prevention of supercontraction damage in boiling bisulfite solutions. The cloth which was treated with the fibers in the bisulfite alone was harsh and gave a positive nitroprusside test, whereas a negative test was obtained with the cloth treated in the presence of ethylene dibromide.

All of these results are evidence for the prominent role of disulfide rupture in supercontraction, and, of course, the lack of supercontraction in the modified fibers indicates that stabilized cross-linkages have replaced the labile disulfide bonds. In regard to the prevention of supercontraction in the boiling bisulfite solutions by the addition of ethylene dibromide, this is exactly analogous to the prevention of supercontraction in alkaline hydrosulfite solutions in the presence of the dihalide. We suggest the following explanation for this behavior: When the fibers are treated with the inorganic reducing agents alone at elevated temperatures, disulfide groups are broken, excessive swelling occurs, and, on a molecular scale, such rearrangement of peptide folds may occur that

TABLE II. TREATMENT OF WOOL FIBERS IN 1.5% SODIUM BISULFITE BATHS ADJUSTED TO pH 8.2*

Addition	Supercontraction (%)
None	27.8
$(CH_2)_2Br_2$†	0.0

* Fibers, along with a piece of wool cloth, were treated in the baths (30:1 ratio) for 1 hr. at the boil.

† 10% ethylene dibromide on the weight of the wool was present in the bath.

an entirely different molecular configuration results. Under these conditions, supercontraction occurs. On the other hand, when cross-linking reagents such as alkylene dihalides are present in the reaction mixture, the sulfhydryl groups which form immediately react with the cross-linking agent to form stable cross-linkages. In this way, before any profound changes can occur through molecular rearrangement of the protein chains, the formation of the new linkages maintains the original cross-linked fiber structure, and, therefore, supercontraction is prevented and the desirable mechanical properties of the original fiber are maintained.

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Very truly yours,

ALFRED E. BROWN
JANET H. PENDERGRASS
MILTON HARRIS

INDUSTRIAL SECTION

Selection of Electric Drives for Looms*

R. J. Demartini† and A. F. Lukens‡

Abstract

This paper outlines a method for calculating requirements of the drive for a weaving loom from knowledge of system constants and without the necessity for extensive testing. When electrical testing is performed the pulsating character of the load must be taken into account in selection of instruments and in interpretation of data. The value of inertia in the successful drive also is discussed.

Introduction

Because the load imposed on motors applied to conventional weaving looms is so complex, including many components of differing characteristics, proper application of such motors has required special skills and laborious techniques. Recently, a program of analytical testing directed at developing a simple, straightforward method for selection of loom drives was completed. A new line of loom motors was developed, and the methods discussed here played a prominent part in the formulation of final specifications. This paper presents a summary of the fundamentals and a discussion of the basic mathematical relations evolved.

The Problem

What is desired is a method whereby, given basic physical constants of a loom, it will be possible to determine the characteristics of the proper drive for it. If the mechanical motions in loom operation can be reduced to a few basic mathematical relationships built around values of the loom constants, the job to be performed by the drive may be clearly defined. With these mathematical tools at hand, the task of selecting the proper motor should be considerably simplified. This is precisely the approach described in this paper.

Ultimately, the drive chosen must conform to the following functional specifications:

1. The drive must have sufficient torque ability to operate the loom even under the extreme conditions exemplified by the high-load break-in period and by those installations in which supply voltage may be low.

2. Operation of the drive must be such as to impart the proper "feel" to the loom—a characteristic which is very important to the trained loom-fixer, and to be evaluated by him. The amount of speed variation pick to pick and the character and magnitude of loom vibration are factors which determine the "feel." This factor has not yet been reduced to quantitative values.

3. The drive must operate on the loom load without overheating.

The Loom

The loom in its earliest form (Figure 1) consisted of any convenient horizontal beam from which the warp, or lengthwise, yarns were hung, a bobbin carrying the "weft" (or "filling"), or crosswise, yarn, and a flat wand the function of which was to separate the warp ends in order that the bobbin might pass between them and to beat the weft into place after each insertion. Stones were often hung as weights at their lower extremities in order to maintain tension in the warp yarns during the weaving operation. To obtain a plain one-up and one-down weave, alternate yarns were moved forward by rotation of the wand. The bobbin was handed across from right to left in the "shed" thus

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† Paper and Textile Division, Industrial Engineering Divisions, General Electric Company, Schenectady, N. Y.

‡ Application Engineer, Lynn Induction Motor Section, General Electric Company, Lynn, Mass.

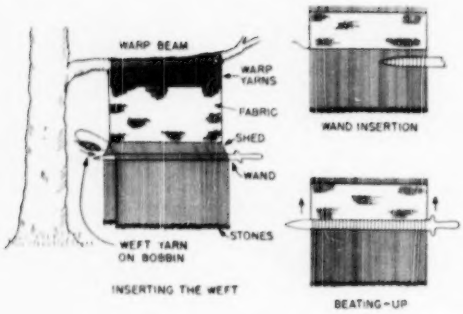

FIG. 1. *Early loom.*

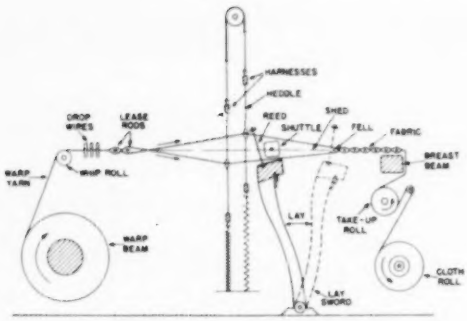

FIG. 2. *Diagrammatic cross-sectional view of loom.*

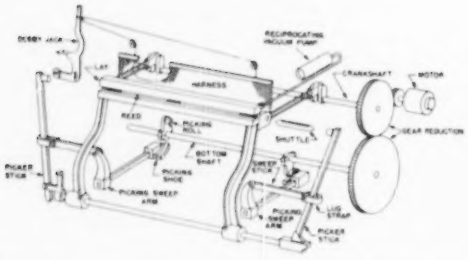

FIG. 3. *Diagrammatic three-dimenstonal view of loom.*

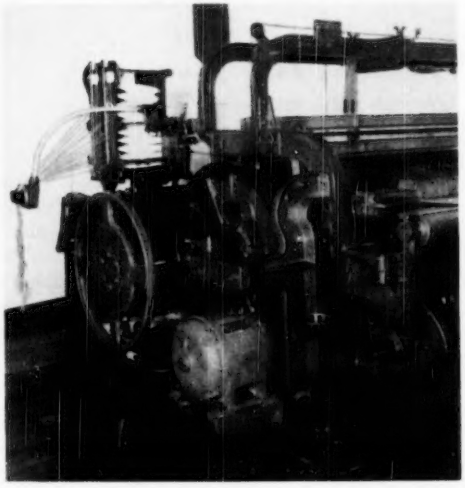

FIG. 3A. *Photograph of a modern weaving loom.*

formed, and the filling yarn thus laid in position was beaten into the fabric. The wand was then withdrawn and reinserted between the ends, this time with the warp yarns which previously lay on the rear side brought forward and those in front dropped to the rear. The bobbin was then passed through the shed from left to right and the wand used to beat the yarn into the fabric. This process was repeated over and over to produce a web, or fabric.

In Figures 2 and 3 are shown the elements of a modern power loom and in Figure 3*A*, a photograph of a modern loom. The same basic functions as practiced in primitive weaving are incorporated in this automatic machine. Warp yarns, which here may number 10–15,000 or more, are many hundreds or thousands of yards long and are wound parallel on a large spool called a "beam." (This term has been carried over from the early loom construction.) This is placed at the rear of the machine, its center-shaft set in bearings to permit rotation as the warp ends are paid off. All of those ends are led up over the guide-roll ("whip-roll"), divided into two equal-numbered systems, and laid over and under the "lease rods." The principal function of lease rods is to separate the closely spaced ends so that the weaver can more easily trace individual ends when tying broken ones. From here, each yarn is fed through its own "heddle," a steel wire with an eye through which the yarn passes in the harness frame. The raising and lowering of the harnesses, and thus of the warp yarns, positions those yarns above and below each weft thread in the order required to obtain the pattern desired in the finished fabric. In Figure 2 there are shown just two harnesses—the requirement for producing a plain one-up and one-down weave. With each "pick," or flight of the shuttle,

one harness is raised and the other lowered. From each harness, the two yarn systems converge to enter the fabric, forming a shed. Between the harnesses and the "fell" (weaving point) of the cloth the ends run through the slots ("dents") formed between closely spaced vertical flat wires of the "reed" (Figure 3). A bell-crank-driven lever, called the "lay," carries the reed forward to push the weft yarn into the cloth and then back out of the shuttle's path. The woven fabric passes over the "breast-beam" and around a positively driven take-up roll and onto a winder, the "cloth roll."

The "shuttle," carrying the weft yarn, is propelled across the loom in flight under the impact of a blow from a rapidly moving lever, called the "picker stick." This stick, usually made of hickory wood, is accelerated rapidly by a cam control and imparts its energy suddenly to the metal-nosed shuttle as it strikes it. The shuttle darts across the loom, decelerating to a stop at the far side under the action of a spring-loaded friction drag in the "box."

In the weaving operation, each of the loom elements performs its function in proper sequence, which is determined by cams and gearing. The order in which the operations occur is as follows:

1. Harnesses are positioned to raise some warp ends and lower others.
2. The lay, carrying the reed, moves to the back position toward the harnesses, and as it approaches the end of its rearward travel, it is decelerated and its direction is then reversed.
3. Struck sharply by the picker stick, the shuttle flies across the loom, trailing the weft yarn behind it, and comes to rest in the box at the far side.
4. Meanwhile, the lay is accelerated forward and the reed pushes the weft yarn into the fabric.
5. As it nears its frontmost position the lay must be decelerated and its direction is reversed once again.
6. A ratchet on the end of the take-up roll is notched forward by a pawl driven from the lay motion.

The cycle is then repeated as the harnesses change position and the next pick is made.

In order to obtain uniformity in the finished product, the warp yarns must be held under tension at all times. A friction brake or other hold-back mechanism is applied to the warp beam to accomplish this.

Often, in order to obtain particular patterns in the fabric, such special motions as the leno or jacquard* attachments are added to the loom. Also, on some looms there is a reciprocating pump (Figure 3) the function of which is to supply a vacuum to an automatic bobbin-changing mechanism. For purposes of this paper the effect on load of such auxiliary equipment is not considered because it is not universally encountered.

Protection

If a warp or filling yarn should break, the loom must be stopped in order to prevent weaving any appreciable length of faulty fabric. Special electric and mechanical detection devices are provided on the loom to signal the occurrence of such a break and cause the clutch to become disengaged.

Occasionally, for any one of several reasons, shuttle speed on a pick may be slower than normal or the shuttle may even fail to complete its flight. If the shuttle has not boxed by the time the lay swings forward to drive the weft yarn home, there is danger that it will be swept forward by the reed and pushed into the fell of the cloth. Many warp yarns would be broken and irreparable damage would be done to the fabric when the "smash" occurred, necessitating a relatively long shut-down for redrawing the broken warp yarns. In order to prevent such an occurrence, means are provided for checking on the position of the shuttle to insure that its flight is true and on schedule early in the lay's forward swing. If the shuttle is not on its true course at this time, the "bang-off" protective mechanism operates to simultaneously declutch the motor and position a restraining rod, thus halting the forward travel of the lay. In order for such a brute-force method of stopping the loom to succeed without causing failure of mechanical elements, the clutch must be disengaged sharply. This occurs at that point in the cycle at which the energy stored in the loom parts is at a maximum.

The Loom Drive

The standard fly-shuttle loom drive consists of a full-voltage starting switch and a single induction motor (Figure 4) the rating range of which is from $\frac{1}{2}$ to 2 h.p. and which is of either 4- or 6-pole design. In order to protect against the possibility that the motors may become plugged with lint from the weave shed atmosphere, they are of totally

* Leno and jacquard motions are mechanisms employed to secure special weaves.

enclosed construction. The sleeve-type, wool-yarn packed bearing, which has proven successful over the years in loom-motor applications, is standard today. The breakdown torque of the loom motor is approximately twice that of the general-purpose motor. The axial length of the motor is kept at a minimum so that it does not influence maximum over-all floor area.

The motor is coupled to the machine through a spur gear reduction and a clutch. Starting and stopping the loom is accomplished by operation of the clutch mechanism, the motor being permitted to run continuously.

Loom Load

The load imposed on the motor by the various parts of the loom can best be studied by considering the energy required to drive each element individually. Since some of the parts have widely varying velocities, it is better to consider them on a torque basis and to refer the torques to the motor shaft. The more important components of the total load are: (1) torque to overcome friction, (2) torque to drive the lay, (3) torque to drive the shuttle, (4) torque to actuate the harnesses, (5) torque to drive the air pump (if included), (6) torque to actuate a leno motion or jacquard head (if any), and (7) torque to actuate many small devices, such as cloth beam, dobby (harness motion control), etc.

For analysis, one pick is considered as one cycle with 0° of the crank shaft taken at front dead-center of the lay and with 180° at back dead-center.

The friction of the loom consists of the actual friction of all bearings, cams, and sliding contacts, and also the constant portion of the unrecoverable part of the energy that goes into driving each part. Friction is assumed to be constant for purposes of analysis, but in practice it varies widely in a relatively short time with changes in lubrication of the various bearings. Figure 5 is a plot of friction torque *vs.* loom speed, derived from 21 tests on a loom of one size and make. Although this machine was well run in and had expert attention while being tested, friction load varied considerably at each speed. Test 10 shows abnormally high friction preceding a bearing seizure, and at the time of the test no distress was noted. The high friction did not show up until the test results were analyzed.

Figure 6 shows in graphic form the torque required to drive each of the various loom parts.

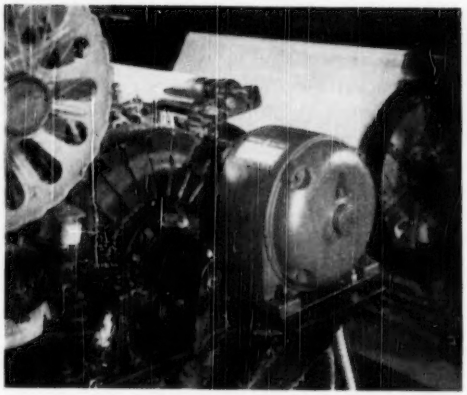

FIG. 4. *Modern loom motor mounted on loom.*

The torque is plotted against lay position, the latter also roughly representing time.

Friction is considered ideally constant and is represented by a horizontal line, *A*.

The lay is a heavy mass oscillating about its center, and requires considerable torque to accelerate and decelerate it. There are two accelerations and decelerations per pick and so the frequency of the torque is twice that of the pickage (curve *B*, Figure 6). During the deceleration, the energy can be recovered and returned to the system either as electric energy or as kinetic energy stored in the effective moment of inertia of the loom. The torque is thus a curve with equal areas above and below the zero line and is a sinusoid as a first approximation. The short, connecting rods and the angularity of these rods introduce some harmonics, which are not important as far as the motor is concerned, although they may be of considerable interest to the loom designer.

The shuttle is struck by the picker stick, which in turn is struck by a cam with a very steep rise. This gives the picker stick its high acceleration and it therefore demands a sharp peak of torque from the drive system. The shape of the cam, adjustment of linkages, firmness of springs in the shuttle box, and probably several lesser factors affect the configuration and amplitude of the torque curve. The curve of Figure 6 labeled *C* is believed to be a fair representation of the actual values, but it can be approximated for purposes of calculation by a single loop of an eighth harmonic sine wave, as shown by the dotted lines.

The torque required to actuate the harnesses (curve *D*, Figure 6) is in most cases not great and its average value is included in the friction component. Unless the loom is fitted with a large number of harness frames and is weaving a complicated pattern that requires the lifting of nearly all of them at once, the variations in torque can be neglected. The load represented by the cloth beam drive, dobby motions, and other lesser elements may similarly be regarded as constant and as a part of the friction factor.

The torque necessary to drive the loom is the summation of these components and is represented by curve *E* of Figure 6.

This torque is supplied from two sources: (1) the motor, and (2) the inertia or flywheel effect of the revolving and oscillating parts of the system. The latter consists of the moment of inertia of the motor, of the revolving parts of the loom, and of the lay. The load at every instant is divided between the motor electrical torque and energy from the rotating parts in varying proportions, depending on the motor speed-torque characteristics and the amount of system inertia. For example, if the loom were driven by an infinitely large synchronous motor, all the torque would be supplied electrically from the power line. The opposite extreme may be represented by a loom equipped with a large flywheel and coasting, with the motor disconnected from the line. In this case the flywheel would supply all of the torque. The actual case, of course, is a compromise between these two cases and the load is divided between the two sources in varying degree, as is illustrated in Figure 7.

Figure 8 is a tracing of an oscillogram of the current and watt input to a motor driving a loom. The similarity between the shape of the measured motor-input curve and that of the calculated total-load curve of Figure 7 is apparent.

Calculations

The above analysis suggests that the motor output can be approximated by calculation provided the components can be treated additively. They may be so treated provided the motor operates on that portion of the motor speed-torque curve which is essentially straight, and this is the case over the usual operating range. A relatively simple loom is considered for the purpose of illustration; additional components for pump, heavy harness, leno, etc., can be added if desired.

As indicated above, friction torque is considered constant and is represented by curve *A* of Figure 6. The torque to drive the lay is treated as a sine wave with a frequency of twice the number of picks and is represented by $B \sin\left(\frac{4\pi P}{60}\right)t$, where B is the peak accelerating torque and P equals the number of picks per minute.

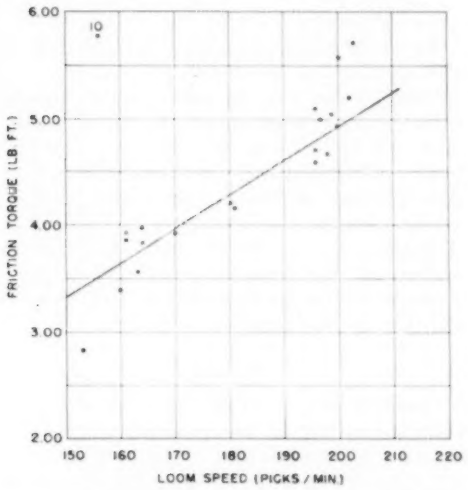

FIG. 5. *Plot of loom friction torque vs. loom speed (based on 21 tests).*

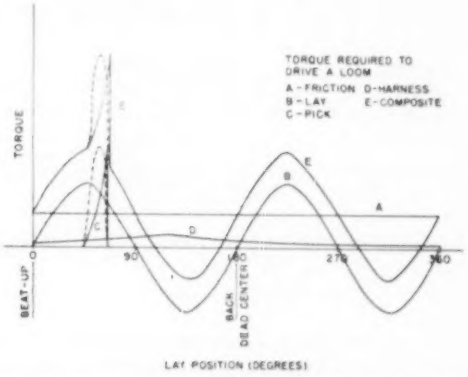

FIG. 6. *An analysis of the nature of components comprising the loom load.*

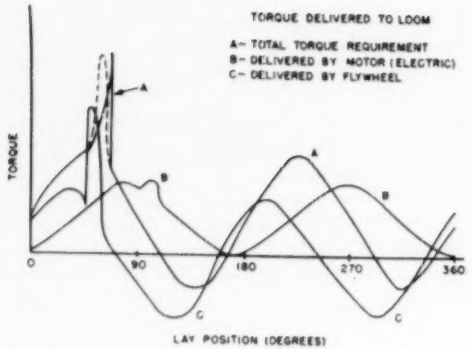

FIG. 7. *An analysis of the manner in which energy is drawn from motor and rotating parts to drive a loom over its cycle.*

The variations in the harness torque are neglected, but the average of the torque wave is included in the friction torque, A.

The torque to produce the pick is assumed to be a single positive loop of an eighth harmonic starting at the peak of the torque wave of the lay. The energy under this wave is made equal to the kinetic energy of the shuttle as it leaves the box, and the maximum value is represented by B'.

Motor torque can be approximated over the useful operating range by Cs, where s is the slip of the motor at any instant and C is the ratio of rated torque to rated slip.

The torque delivered by the flywheel is $I\,ds/dt$, where I is a function of Wk^2 (inertia) and ds/dt is the acceleration of the flywheel.

These components of torque are equated and the differential equation is reduced to the following:

$$T_{max} = A + \frac{B}{\sqrt{1 + \left(\frac{P \cdot Wk^2 \cdot N_o^2 \cdot S_{fl}}{7.75 \cdot 10^6 R}\right)^2}}$$

$$+ \frac{B'}{\sqrt{1 + \left(\frac{4P \cdot Wk^2 \cdot N_o^2 \cdot S_{fl}}{7.75 \cdot 10^6 R}\right)^2}} = A + D + F;$$

$$T_{rms} = (A^2 + 0.5B^2 + 0.048F^2 + 0.04AD + .03DF)^{\frac{1}{2}};$$

$$N_{min} = N_o\left(1 - \frac{T_{max}}{C}\right).$$

T_{max} is the maximum torque imposed on the motor which is used in conjunction with the breakdown torque to determine the ability of the motor to carry the load under adverse conditions. T_{rms}, the root-mean-square of the motor output, is used to determine motor heating. N_{min}, the minimum speed of the motor at the instant of heaviest load, is used in estimating loom operation.

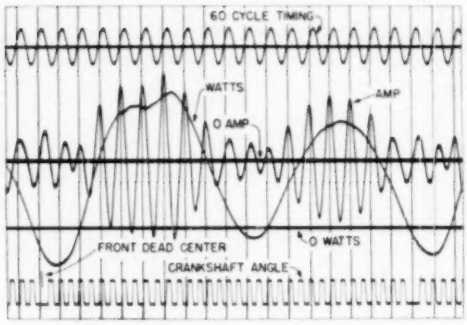

FIG. 8. *Oscillogram taken in loom test.*

Other terms used in the above equations are defined as follows: A = friction torque, B = peak torque to accelerate lay, B' = peak torque to accelerate shuttle, P = number of picks per minute, Wk^2 = total system Wk^2 referred to motor, N_o = motor synchronous speed, R = motor h.p. rating, S_{fl} = motor rated slip at full load, C = ratio of motor rated torque to rated slip, D = peak motor torque to drive lay, and F = peak motor torque to drive shuttle.

(See Appendix I for complete derivation of the above equations.)

All of the parameters, with the exception of friction torques, can be obtained by weighing and measuring; they may be well known to loom designers. The friction must be estimated or determined by test. These equations lend themselves to fairly rapid columnar calculation, and, although only approximate, they are sufficiently accurate for motor application, as proved by comparison with oscillographic tests. By their use it is not difficult to compare the operation of motors with various combinations of characteristics and to select the one with well-balanced performance.

Testing

Looms are tested to check their motor operation and weaving ability, as previously outlined. In addition, tests can be used by the mill operator to determine whether the loom fixer's adjustments hold friction and peak torques within limits anticipated by the loom designer.

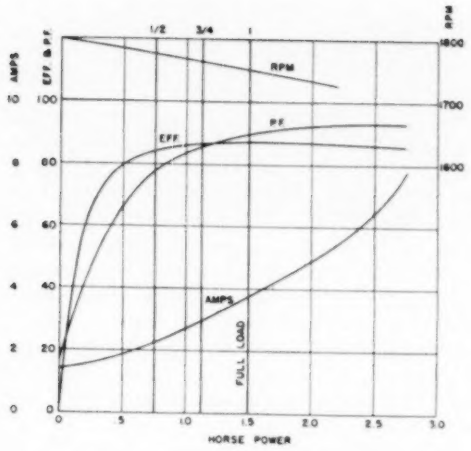

FIG. 9. *Typical loom-motor characteristic curves (steady state).* (P. F. = *power factor.*)

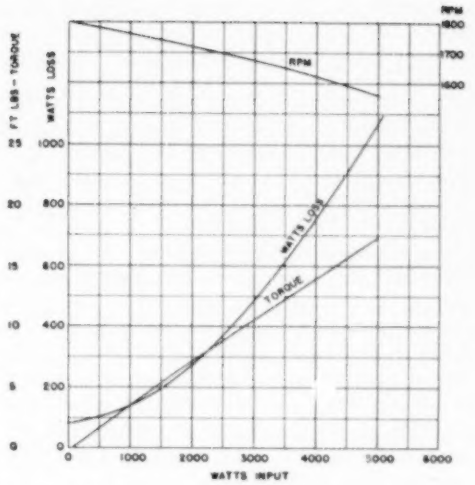

FIG. 10. *Typical loom motor curves of torque, speed, and watts loss* vs. *watts input, based on data in Figure 9.*

From the oscillogram (Figure 8) it is apparent that watts input to the motor and the current input vary widely during different parts of the cycle. Ordinary meters connected to the circuit show wide needle swings and unless properly read give meaningless results. However, reliable results can be obtained if proper precautions and techniques are employed.

Practical quantitative values descriptive of loom and motor operation are deduced from motor watt-input measurement with due recognition of the two principles: (1) that at any instant the input to the motor is the sum of motor output and motor losses; and (2) that over a period of time the average input to the motor is the sum of the average output plus the losses of the motor at the *rms* load.

Input can be measured in various ways, but the one that probably gives the greatest accuracy and the most complete information is an oscillographic recording of watts input to the motor. The oscillograph should be one that shows watts as an integrated curve and not as an envelope of an A.C. wave. The average of the watt curve (Figure 8) is the average watt input to the motor and can be obtained by measuring ordinates or by means of a planimeter.

The *rms* of the watt trace can be calculated by measuring the ordinates, squaring them, averaging the squared values, and extracting the square root—a tedious process. The *rms* value can also be determined by the use of an Amsler Mechanical Integrator, a device that reads squared areas in the same manner that an ordinary planimeter reads areas, and the *rms* value can be calculated as easily as the average.

The next step is to determine the watts loss of the motor. This can be done by referring to a test of the motor taken under steady load conditions (Figure 9) and determining the loss at the same watts input. A curve such as that in Figure 10 is more convenient to work from. This is computed from efficiency data of Figure 9 and is a plot of watts input *vs.* watts loss. In a similar manner, torque *vs.* watts input and speed *vs.* watts input may also be plotted (Figure 10). The average output of the motor is then the difference between average watts input and the watts loss and can be converted to horsepower by dividing by 746 or to torque by multiplying by $\frac{7.04}{\text{av. r.p.m.}}$. This is the friction torque of the loom.

Since the friction torque varies greatly, as illustrated in Figure 5, a comparison of motors on the basis of tested losses is fruitless unless the motor operation is referred to a common friction load. This is done by determining the difference, a, between the friction determined in a particular test and the accepted nominal value. Let rms_a be the tested *rms* output of the motor and F_a the tested

average output. The corrected *rms* output, rms_c, is:

$$rms_c = \sqrt{rms_o^2 + 2aF_o + a^2}.$$

From the corrected *rms* output the corrected losses are determined from the curve (Figure 10) plotted from data obtained under steady load conditions.

Peak values of torque and maximum and minimum values of speed can be determined, at least approximately, from Figure 10.

Loom motors can be tested without the use of an oscillograph with only a slight loss of accuracy and detail. The average watt input can be read on a polyphase wattmeter by reading the maximum and minimum positions of the needle as it swings through a rather wide range and then averaging the two readings. A better method is to use a watt-hour meter, counting the revolutions of the disc for a minute or so and determining the average watts over this period of time.

The *rms* current can be measured by an ordinary electrodynamic or soft-iron ammeter by noting the maximum and minimum positions of the needle and taking the reading half way between the extremes. This is the *rms* value, since the scale of such an instrument is divided in *rms* units. Calculations based on such test results are the same as those outlined above except that the *rms* load is determined from a current curve rather than from a watt curve. A hot wire ammeter can also be used to advantage because the needle swings are not as great as with the conventional type of indicating instrument. However, hot wire instruments have practically no overload capacity and are thus very prone to require frequent recalibration.

A fair approximation of peak torque can be obtained by measuring the peak value of watts input with a pointer-stop polyphase wattmeter. With this type of instrument the needle is held up by an adjustable stop so that it moves from the stop only during the maximum part of the cycle. By using such a meter, the effect of the inertia of the meter itself is eliminated and a true peak value is observed. If a pointer-stop meter is not available, an ordinary instrument can be used by removing the cover glass and holding the needle in an elevated position with some small tool such as the blade of a penknife. This value of peak watts is used in the same manner as is that read from an oscillogram.

A sample calculation of each type of measurement is given in Appendix II.

Effect of Wk^2

As explained above and illustrated in Figure 7, the torque required to drive the loom is supplied in part from the power line and in part from the rotating parts of the system. The division of load varies, depending upon the amount of flywheel effect in the mechanical system and the slope of the motor speed-torque curve. Since the speed of the flywheel must drop to give up energy, it may be deduced that a motor with a sloping speed-torque curve is indicated. However, since the efficiency of a motor decreases with decreasing speed, motor input (the sum of output and losses) tends to increase. Thus, the gain expected from decreasing the load on the motor by letting the inertia do more work is offset to some degree by additional motor losses.

For this reason, a low-slip, highly efficient motor with high-breakdown torque can be just as efficient and give just as stable operation as one with greater Wk^2 but with lower efficiency, greater slip, and with lower-breakdown torque. The operation of the loom is apparently exactly the same in both cases.

Increasing Wk^2 always reduces the amount of load on a motor of a given electrical design and reduces the motor losses as well as its speed variations when driving a pulsating load. The curve shown in Figure 11 illustrates how the losses of a given design of motor were reduced by the increasing of Wk^2. It is apparent that the amount of reduction is appreciable but that the gains diminish after a reasonable amount of flywheel has been added. A motor with a built-in flywheel is shown in Figure 12.

The reduction in losses is so great that it is often entirely feasible to reduce the motor size one whole step, and still satisfy the requirements of good motor application and loom operation.

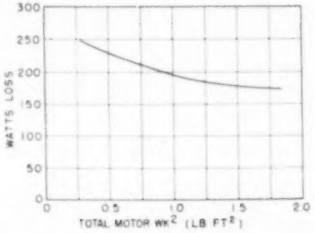

FIG. 11. *Curve illustrating effect of inertia on loom motor losses.*

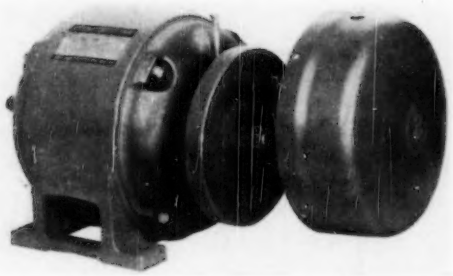

FIG. 12. *Flywheel loom motor with cover removed.*

Another consideration favoring inclusion of appreciable rotating inertia on the motor shaft is that 1,200-r.p.m. motors may be substituted for 1,800-r.p.m. motors without an increase in speed variation. This is not possible with conventional motors because the effective motor rotor Wk^2 which varies with the square of the motor speed is appreciably less when lower-speed motors are used.

Motor Selection

In order to be sure that the motor will drive the loom without distress, two criteria are used: (1) the peak torque under maximum load on the motor should not exceed $\frac{2}{3}$ of the breakdown torque of the motor; and (2) the motor losses should not exceed the steady-state load losses which give a reasonable temperature rise.

By limiting peak torque to about $\frac{2}{3}$ of breakdown torque, sufficient margin is provided to insure satisfactory operation under such adverse conditions as 10% undervoltage and temporary load increase of about 20%, as might be experienced during the loom break-in period. This safety factor assures that the speed will not drop so much that the picking will become erratic.

Loom motors are rated 40°C rise on the windings at rated horsepower, this temperature being measured by a thermometer during operation at rated load and under steady-state conditions. However, traditionally, motors have been applied on the pulsating loom load to operate at about 55°C rise on the windings. (Overload protectors have always been selected in the range of 140%–160% of rated full-load current.) Although the method of rating and applying motors to looms differs from that for standard motors, the application specification that winding rise should not exceed 55°C is the same as that for a conventional totally enclosed motor. This is the maximum temperature rise considered for long trouble-free insulation life. As in any motor of this size, the outside temperature is considerably less than that of the winding and is generally in the 40°C rise range. Furthermore, this has become the practical limit in the minds of many, on the basis that a higher temperature affects the humidification around the loom. Therefore, a practical rule of application that insures meeting both requirements is:

Select a motor so that the temperature rise exceeds neither 40°C on the frame nor 55°C on the windings. Both temperatures are to be taken with mercury thermometers or by using an equivalent method.

The temperature rise of a motor on the loom cycle can be determined by comparing the *rms* losses, determined as outlined above, with the losses for a given temperature rise under steady-state conditions. This eliminates the necessity of conducting a heat run on the loom cycle.

Conclusions

1. The loom load is of a pulsating character, and the motor applied must have characteristics different from those of general-purpose machines. Energy required at every instant must be supplied in part by electrical air-gap torque and in part from energy stored in Wk^2 (inertia).

2. Loom motors which give equivalent performance may be made with a wide range of designs, provided the characteristics are properly balanced.

3. The addition of a sizable flywheel reduces motor load, makes it possible to reduce the rating of the motor in some cases, and makes the operation of 1,200-r.p.m. and 1,800-r.p.m. motors equivalent.

4. Knowing only the basic constants of a loom and motor, performance of the combination may be calculated.

5. Motor tests on looms give results capable of reliable interpretation. Suitable instruments are: (*a*) an electrodynamic or soft-iron type of ammeter to read *rms* amps., (*b*) a watt-hour meter or a polyphase wattmeter for reading average watts, (*c*) an A.C. voltmeter to indicate line voltage. An oscillograph may be used instead of these three instruments for more precise results.

6. Friction load varies from loom to loom and from time to time on a given loom. This demands that a representative value of friction be established and that all tests be corrected to a common base. In comparative testing, individual readings must be corrected to a nominal value before drawing conclusions.

Appendix I

This method of calculation of the total motor output is based on the assumption that the load consists of a constant part (broadly, friction), a sinusoid for accelerating the lay, and a single positive loop of an eighth harmonic for the pick. The torque is supplied electrically from the motor and also from the flywheel. It is further assumed that the motor speed-torque curve is a straight line over the operating range.

The following must be known in order to make the calculation:

For the loom:

A = friction torque
H = weight of the shuttle
L = distance the lay moves
P = number of picks per minute
V = shuttle velocity as it leaves the box
W = weight of lay
Wk_L^2 = Wk^2 of the revolving parts of the loom (referred to the motor)

For the motor:

N_s = synchronous speed of the motor
R = horsepower rating of the motor
S_{fl} = full-load slip of the motor
Wk_M^2 = Wk^2 of the motor revolving parts
C = motor torque constant (see equation (13))

The following symbols are also used:

B = max. torque to drive lay
B' = max. torque to pick shuttle
D = peak motor torque to drive lay
E = energy of shuttle
F = peak motor torque to drive shuttle
N = instantaneous motor speed
N_{min} = minimum motor speed
S = instantaneous motor slip
S_a = motor slip for friction
S_1 = motor slip for lay
S_2 = motor slip for pick

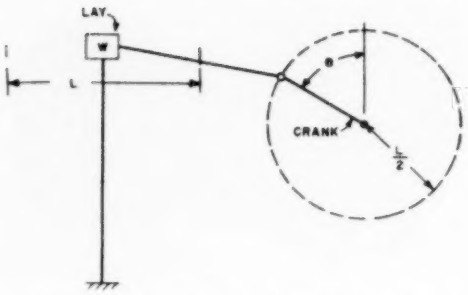

FIG. 13. *Diagram of mechanics of lay drive.*

T_{fl} = motor full-load torque
T_L = torque to drive lay
T_{max} = maximum torque motor delivers
T_{rms} = *rms* torque motor delivers
T_s = torque to drive shuttle
Wk^2 = total Wk^2 referred to motor = $Wk_L^2 + Wk_M^2$
l = instantaneous movement of lay
t = time
α = angle at which pick occurs
θ = crank angle
ω = angular velocity (radians/sec.) = $\frac{2\pi P}{60}$

Torque to Drive the Lay

The lay is assumed to move in a straight line and to have an infinitely long connecting rod. (See Figure 13.)

The displacement of the lay from the center at any instant is:

$$l = \frac{L}{2}\sin\theta = \frac{L}{2}\sin(1-S)P\cdot\frac{2\pi t}{60} = \frac{L}{2}\sin(1-S)\omega t. \quad (1)$$

Acceleration of lay:

$$a = \frac{d^2l}{dt^2} = -\frac{L}{2}(1-S)^2\omega^2\sin(1-S)\omega t. \quad (2)$$

Torque to drive the lay (= − mass × acceleration × radius × cos θ):

$$T_L = \frac{WL^2\omega^2(1-S)^2}{4g}\sin(1-S)\omega t\cdot\cos(1-S)\omega t. \quad (3)$$

Since $(1-S)$ and $(1-S)^2 = 1$, then

$$T_L = \frac{WL^2P^2}{23500\cdot N_s}\sin 2\omega t = B\sin 2\omega t. \quad (4)$$

Torque to Drive the Shuttle

The torque to drive the shuttle is assumed to be a single positive loop of an eighth harmonic.

Let E = energy of shuttle leaving the box

$$= \frac{HV^2}{2g}; \quad (5)$$

E = average force × distance.

$$\text{The distance} = \left(\frac{1}{16}\right)(2\pi)\left(\frac{L}{2}\right)\sin\alpha$$

$$= \frac{\pi}{16} L \sin\alpha. \quad (6)$$

(See Figure 14.)

$$\text{Therefore, the average force} = \frac{E}{\frac{\pi}{16}\sin\alpha}. \quad (7)$$

Torque = force × radius

$$= \frac{E}{\frac{\pi}{16} L \cdot \sin\alpha} \times \frac{L}{2}\sin\alpha = \frac{8E}{\pi}. \quad (8)$$

$$\text{Max. torque} = \frac{\pi}{2}\frac{8E}{\pi} = 4E \text{ (referred to crankshaft)}, \quad (9)$$

where $\frac{\pi}{2} = \frac{\text{peak}}{\text{average}}$ of sine wave.

$$T_{s\,max} = \frac{4EP}{N_o} = B' \text{ (referred to motor shaft)}, \quad (10)$$

and

$$T_s = B' \sin 8\omega t \Big]_{3\pi/16}^{5\pi/16}; \quad (11)$$

that is, one positive loop of a sine wave extending from $t = \frac{3}{16}$ to $\frac{5}{16}$, because it is assumed that the pick occurs when the torque required to drive the lay is at a maximum.

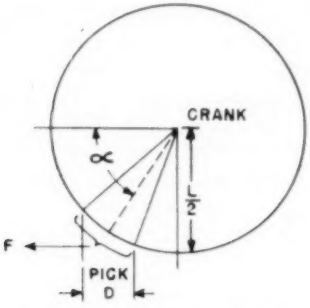

FIG. 14. *Diagram illustrating portion of crank cycle devoted to picking.*

Motor Electrical Torque

The electrical torque of the motor = CS, (12)

where

$$C = \frac{T_{ft}}{S_{ft}} = \frac{5250R}{S_{ft}N_o}. \quad (13)$$

Moment of Inertia

Torque delivered by the moment of inertia of system

$$= \frac{Wk^2}{306}\frac{dN}{dt} = \frac{Wk^2N_o}{306}\frac{d(1-S)}{dt}$$

$$= -\frac{Wk^2N_o}{306}\frac{dS}{dt} = -I\frac{dS}{dt}, \quad (14)$$

where

$$I = \frac{Wk^2N_o}{306}. \quad (15)$$

Maximum Torques

Equating the expression for total load torque with that for total driving torque:

$$A + B\sin 2\omega t + B'\sin 8\omega t = CS - I\frac{dS}{dt}. \quad (16)$$

Since the equation indicates linear relationship, it can be broken down to:

$$A = CS_o; \quad (17)$$

$$B\sin 2\omega t = CS_1 - I\frac{dS_1}{dt}; \quad (18)$$

$$B'\sin 8\omega t = CS_2 - I\frac{dS_2}{dt}; \quad (19)$$

$$S = S_o + S_1 + S_2. \quad (20)$$

The similarity of equations (18) and (19) to the usual equation of harmonic current is apparent. (The symbols used in equations (21) and (22) are the usual electrical ones.)

$$E\sin\omega t = iR - L\frac{di}{dt}. \quad (21)$$

The solution given in any text on alternating currents is:

$$i = \frac{E}{\sqrt{R^2 + (L\omega)^2}}\sin\left(\omega t - \tan^{-1}\frac{L\omega}{R}\right). \quad (22)$$

By comparison, the following can be written from equations (17) through (22):

$$T = A + \frac{BC}{\sqrt{C^2 + (2I\omega)^2}}\sin\left(2\omega t - \tfrac{1}{2}\tan^{-1}\frac{2I\omega}{C}\right)$$

$$+ \frac{B'C}{\sqrt{C^2 + (8I\omega)^2}}\sin\left(8\omega t - \tfrac{1}{8}\tan\frac{8I\omega}{L}\right); \quad (23)$$

$$T_{max} = A + \frac{B}{\sqrt{1 + \left(\frac{PWk^2N_s^2S_{ft}}{7.75 \cdot 10^6 R}\right)^2}} + \frac{B'}{\sqrt{1 + \left(\frac{4PWk^2N_s^2S_{ft}}{7.75 \cdot 10^6 R}\right)^2}} \quad (24)$$

$$= A + D + F. \quad (24a)$$

rms Torque

The equation of *rms* torque is:

$$T_{rms} = \left(\frac{\omega}{2\pi}\left[\int_0^{3/16(\pi/\omega)} (A + D\sin 2\omega t)^2 dt + \int_{3/16(\pi/\omega)}^{(2\pi/\omega)} (A + D\sin 2\omega t)^2 dt + \int_{3/16(\pi/\omega)}^{3/16(\pi/\omega)} (A + D\sin 2\omega t + F'\sin 8\omega t)^2 dt\right]\right)^{\frac{1}{2}}, \quad (25)$$

which reduces to

$$T_{rms} = (A^2 + 0.5D^2 + 0.048F'^2 + 0.04AD + 0.03DF)^{\frac{1}{2}}. \quad (26)$$

Minimum Speed

$$\text{Min. speed} = N_{min} = N_o\left(1 - \frac{T_{max}}{C}\right). \quad (27)$$

Correction of Motor rms *Output to Nominal Friction* (*See Figure 15*)

Let F_o = friction as tested, F_c = nominal friction, rms_o = root-mean-square of output as tested, rms_c = root-mean-square of output as corrected, and $a = F_c - F_o$. (28)

By definition,

$$rms_o^2 = \int_o^{x_o} \frac{y^2}{x_o} dx, \quad (29)$$

and

$$F_o = \int_o^{x_o} \frac{y}{x_o} dx. \quad (30)$$

Then,

$$rms_c^2 = \int \frac{(y + a)^2 dx}{x_o} = \int \frac{y^2}{x_o} dx + 2a\int \frac{y}{x_o} dx + a^2\int \frac{dx}{x_o} \quad (31)$$

$$= rms_o^2 + 2aF_o + a^2; \quad (32)$$

$$rms_c = \sqrt{rms_o^2 + 2aF_o + a^2}. \quad (33)$$

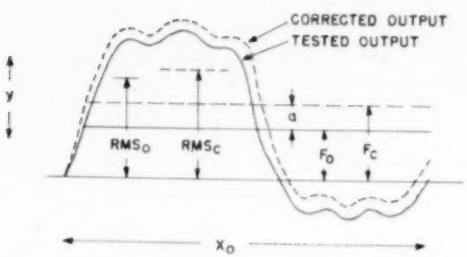

FIG. 15. *Correction for nominal friction.*

Appendix II

Sample Calculation of Test Results

Test Data

(1) Motor rating = 1½ h.p.
(2) Picks/min. = 202.
(3) Average watts (oscillogram) = 1,600.
(4) Average watts (indicating meter) = 1,620.
(5) *rms* watts (oscillogram) = 2,160.
(6) *rms* amps. (indicating meter) = 6.5.

Calculation of Oscillogram Test Results

(7) Watts loss (Figure 10) = 305.
(8) Average output = 1,600–305 = 1,295.
(9) Average torque = $\frac{1,295}{746} \times \frac{5,250}{1,750} = 5.25$.
(10) *rms* torque (Figure 10) = 7.5.
(11) Assumed average torque at 202 picks (Figure 10) = 5.00.
(12) Average torque correction (a) = 5.00–5.25 = − 0.25.
(13) Corrected *rms* torque = $rms_c = \sqrt{7.5^2 - 2(0.25)(5.25) + (0.25)^2} = 7.4$.
(14) Corrected losses (Figure 10) = 295.

Calculation of Indicating-Instrument Test

(15) h.p. at 6.5 amps. (Figure 9) = 2.5.
(16) Efficiency at 2.5 h.p. (Figure 9) = 0.86.
(17) *rms* loss = $2.5 \times 746\left(\frac{1-0.86}{0.86}\right) = 305$ watts.
(18) Average output = 1,620–305 = 1,315 watts.

Then proceed through steps (9) to (14) inclusive.

(*Manuscript received September 21, 1949.*)

Continuity in Textile Research*

J. H. Dillon†

THE CARDINAL IMPORTANCE of continuity in any research program is now becoming recognized in many industrial fields. In the textile industry, however, this principle appears not to have received the attention which it deserves. With that industry standing upon the threshold of what should be a real research era, it appears particularly important at this time for protagonists of research to stress the necessity of continuity of support of sound research programs in order for the industry to realize fully the long-range practical benefits. They should, furthermore, studiously avoid over-optimistic predictions, particularly guarantees of immediate practical results. Rather, they should place before textile executives the unvarnished facts, as deduced from experience with research in other industries. Along this line of thought, it seems advisable to consider some of the basic requirements of a successful research program, all of which may be considered as the elements of the broad principle of continuity.

Before any company embarks upon a scientific research program either individually within its own laboratories or cooperatively through an industry-supported organization, management should decide, first of all, what sort of research program it wishes to undertake or support. In the broader sense, industrial scientific research programs may be classified as follows: (1) research for publicity purposes; (2) production trouble shooting; (3) quality and process control; (4) short-range development with specific and limited objectives, generally aimed at product and process improvement; (5) longer-range applied research on new materials, processes, and products; (6) long-range fundamental research directly or indirectly related to the field of the company's interest; (7) support of academic research within university laboratories with the aim of increasing the general fund of research knowledge and accelerating the training of scientists for industry.

It may seem unprofessional to include the first item—research for publicity purposes. Yet, many an industrial laboratory started essentially on this basis, and later went into true productive research when some young scientist refused to be a museum piece and demonstrated what could be accomplished with a combination of training, brains, enthusiasm, and a little equipment. Furthermore, there is no reason why the research accomplishments of an industrial laboratory should not be used in its advertising and sales campaigns, providing this is done without exaggeration or distortion and without loss of the professional dignity of the research staff. Deliberate development of a research laboratory *for publicity alone*, of course, is decidedly unwholesome and would never be advised by a reliable scientist. However, a research advisor would be unrealistic were he to neglect the publicity value of research in setting up an industrial laboratory.

The history of the growth of research effort in most of our industries has followed the sequence of items (2) to (7). Often the initial "trouble shooting" was done by non-technical personnel until successful use of the more scientific methods of quality and process control indicated the need for technically-trained people for trouble-shooting work also. Frequently, the technical trouble shooters gradually became development men, thus initiating phase (4)—short-range development.

It was quite natural, of course, to find many small companies bogged down in this phase (4) because of the great cost of progressing to the longer-range work of phase (5)—longer-range applied research. It is a little surprising, however, to find many large firms still in this category, particularly within the textile industry; even more so to observe the number of large organizations which have at one time or another embarked upon ambitious programs involving phases (5)—longer-range applied research—and (6)—long-range fundamental research—but have slipped all the way back into phases (2) and (3)—trouble shooting and control. While it is customary to lay the blame for these recessions in research progress upon management, it must be recognized that the scientist and his supporters have often been at fault, particularly in their failure to present to industrial executives the bare facts concerning the costs and

* Presented at the 20th Annual Meeting of Textile Research Institute, New York, December 2, 1949.

† Director of Research, Textile Research Institute and The Textile Foundation.

time required to realize full production from a research program. In any event, every major recession in research progress within an industrial laboratory or an industry-group-sponsored organization constitutes a waste of money, time, and scientific man power. Furthermore, each setback discourages other firms from attempting to advance their research programs; that is, the continuity of research progress is broken to the serious detriment of individual firms and the industry at large. Conversely, those firms who have proceeded upon good advice, technical or otherwise, to build their research organizations and programs gradually, following in a general way the natural sequence of phases (2) to (7), now find themselves in an excellent position to reap the harvest of research benefits almost invariably resulting from observing thus the principle of continuity.

But, forgetting the past, let us say that the research advisor and the mill executive have taken properly the first step in developing the research attack by deciding what type of program or combination of programs is desirable initially and how the program should develop in the future. The next important step is the acquisition of a few key research scientists upon whose shoulders must rest the vital and difficult task of building a research staff. The term "building" is used advisedly; a research group must be *built* gradually and carefully—not precipitously *bought* on the open market. While this staff-building campaign is taking place, the research program must be developed concomitantly, and, strangely enough, long before staff and laboratories are considered complete, good and sometimes useful results will be observed emerging in rapidly increasing volume. It will be necessary now and then, of course, to release a man who does not fit into the program and sometimes change the program where it is found wanting. Then, too, some sort of laboratory must be provided, with a reasonable amount of equipment. But the good research man with mediocre equipment is much to be preferred to the mediocre man with the most expensive and shiniest chrome-plated instruments, if a choice must be made. Obviously, the essence of this successful approach to research is continuity. When this continuity is broken by severe reductions in staff or unreasonable curtailment of supplies and equipment, it must be recognized that any future rebuilding may take as long, or longer, than the original task of building, and it will undoubtedly be more costly. This is not an idealistic or theoretical statement; it is based upon the experience of all of our presently successful industrial research organizations. Obviously, this principle applies equally well to industry-group-supported organizations.

If the research man is the basic element in research, it goes without saying that a wholesome research personnel policy must be set up. The scientist is by training a professional and by nature an individualist. Often his viewpoint differs somewhat from that of the production or financial expert. However, if the mill manager recognizes this difference and does not insist on making over the scientist, he will find him, on the average, an inherently reasonable person who will work hard and loyally on the team. It should not be surprising to find that a scientist has the capacity for enjoying a reasonable standard of living and, therefore, expects to be properly remunerated and treated as a human being. There is nothing holy about research or a research scientist; removal of the mystery with which he is so often clothed can go a long way toward his integration into the over-all organization of the company.

The matter of research appropriations deserves some comment also, in the light of the principle of continuity. In general, experience indicates that appropriations should grow with the size and scope of the research group. Seldom is there to be found a research man who will admit to possession of an appropriation which is too large; yet there have been numerous instances where this has been the case. Part of the answer to this problem seems to lie in the development of a "planning group" which includes both non-technical management and the various key research leaders. Such a group can usually balance the research needs of the company against the funds necessary for their fulfillment. One of the first lessons which a "planning group" must learn is that doubling a research expenditure seldom produces useful results at double the rate, particularly during the growth period of a research organization.

It is not the purpose of this brief discussion to propose an ideal plan for a research and development organization. Many excellent organization plans are in operation and have been described, but each plan is a function of the characteristics of the particular company or mill involved. Yet, the principle of continuity maintains its importance throughout the long process of integration of research, development, production, and sales. There is an increasing tendency

to bring experienced technical executives into the higher echelons of management, and it appears that the textile industry is beginning to realize that a good scientist is not always a poor executive; in fact, the scientist-executive often can make significant contributions in the area of policy-making. Although the nature of the scientist's work demands that he be both imaginative and creative, it is not at all well understood that the scientist must constantly be examining and re-evaluating his results and the conclusions drawn from them. His role in management, therefore, is often that of constructive conservatism.

In summary, an attempt has been made to state a few elementary laws, grouped under the general principle of continuity, which should be observed in developing a successful industrial research attack. The very simplicity of these laws almost seems to preclude the necessity of their enunciation. However, the fact that many violations of them have occurred in the past, often with disastrous results, suggests that their discussion is worth while. The textile industry stands to profit just as greatly from fundamental and applied research as have other industries if it is willing to learn from example and observe the basic tenets of the principle of continuity, both in the growth and prosecution of its research attack.

Presentation of Certificates to Founding Fellows of T. R. I., December 1, 1949

It is fitting that TEXTILE RESEARCH JOURNAL *should be cognizant of the honor bestowed on William D. Appel, Frederic Bonnet, and Edward R. Schwarz for their outstanding achievements in the fields of research and education. At a luncheon ceremony, December 1, 1949, held in connection with the Annual Meeting of Textile Research Institute, Inc., certificates were awarded naming these gentlemen Founding Fellows of T.R.I. The citations which follow were presented by John H. Dillon, Director of Research of T.R.I. and The Textile Foundation. After each citation A. G. Ashcroft, President of the Institute, presented the certificates naming each individual a Fellow of Textile Research Institute.*—Editor

Ladies and Gentlemen:

It has always been our policy to confine the luncheon program on "Scientific Day" at T.R.I. annual meetings to the simple but enjoyable functions of eating and informal conversation. Today, however, we are about to break that precedent but, I am certain, in a manner which you will enjoy and for a very important purpose—the presentation of certificates of Fellowship of T.R.I. to the first three textile scientists to receive this honor. As you have already learned from recent press announcements, the membership grade of Fellow of T.R.I. was established in order to recognize extraordinary achievement in textile technology, research, and education.

I certainly feel that the T.R.I. Committee on Fellowship is to be congratulated in its selection as Founding Fellows of these three distinguished (and handsome) gentlemen who sit at this table with Mr. Ashcroft, our president. It so happens that our three Founding Fellows have made their respective major contributions in the textile research field through their work in government, industrial, and university laboratories. But, in a broader sense, each of them

has been a teacher as well as a research scientist and technologist. All of them are known for their fine human qualities and have the affection and respect of their many friends and associates.

We have but a few minutes to devote to this simple act of presentation but, fortunately, each of our Founding Fellows is so well known and recognized for his accomplishments that any long recital of them would be redundant. Thus, while my honor in being chosen to participate in this presentation is perforce brief, it is nevertheless a great and pleasant privilege. Incidentally, this presentation is unique in that, while we realize that each of our Founding Fellows is a polished and effective speaker and all of us would like to have a long speech from each, we are not requiring a response of acceptance from any of them. I confess that I, like our good Committee, find myself entirely incapable of distinguishing among the accomplishments of these three gentlemen; hence, I shall discuss their individual records and achievements in the alphabetical order of their surnames.

William D. Appel

"A" stands for *Appel*. In fact, he was an "A" student at the University of Chicago, where he majored in zoology but also studied physics, mathematics, and chemistry, taking graduate courses in the latter. He began his professional career before entering the University with the U. S. Biological Survey in 1912 as an Assistant in Economic Ornithology. He is still an authority on bird life; ornithology is one of his many outdoor hobbies. For the period 1914–17 he was an assistant in zoology at the University of Chicago while pursuing his studies. He next served as chemist in charge of the analytical laboratory of the Federal Dyestuff and Chemical Company of Kingsport, Tennessee. He then directed his career definitely toward dye chemistry, holding successive positions with Ault and Wiborg of Cincinnati, the Newport Company of Milwaukee, and finally the National Bureau of Standards, the staff of which he joined as a dye chemist in 1922. His work on spectrophotometric transmission measurements on dye solutions, dyeing methods, and testing of dyes, especially of the action of light on dyed textiles, brought him in intimate contact with the textile industry and with the work on light fastness of the American Association of Textile Chemists and Colorists, which he joined in 1924. His interest in textiles increased rapidly and so did his influence and leadership in the work of several committees of this Association, in which he was active. The Association recognized the importance of his work at the National Bureau of Standards and established a research associateship at the Bureau under his direction.

Mr. Appel was promoted to his present position of Textile Technologist and Chief of the Textiles Section of the Bureau in January, 1929. He attended the first meeting of the Textile Research Institute (in Boston in May, 1929), then known as the Textile Research Council, and presented a paper entitled "Quantitative Relation Between the Spectral Reflection of Textile Dyeings and the Amount of Dye Used." Under his leadership the work of the Textiles Section expanded rapidly and many modern techniques and new knowledge in the fields of engineering, chemistry, physics, mathematics, statistics, photochemistry, spectroscopy, microscopy, and electronics were applied vigorously to fundamental, applied, and consumer research problems on textiles. Since 1929, he has published some thirty papers and reports, and, in addition, over 600 technical papers and reports have been published by the members of his staff. He received the War Department Certificate of Appreciation for Patriotic Services during World War II and also the American Standards Association Certificate of Appreciation for services on war standards (World War II).

Mr. Appel has a remarkable record of activity in the affairs of the many professional societies of which he is a member. For example, he served for 4 years as chairman of the Dye Division of the American Chemical Society. He was president of the American Association of Textile Chemists and Colorists in 1944, 1945, and 1946, has been chairman of the Sub-Committee on Textile Test Methods of Committee D-13 of A.S.T.M. since 1929, chairman of the Federal Specifications Board's Technical Committee on Textiles since 1941, and chairman of the Intersociety Council for Textile Research since 1944. He has been a member of the Advisory Committee for Scientific Research of The Textile Foundation for a number of years, and a member of Textile Research Institute since its origin in 1930 as the U. S. Institute for Textile Research, serving as chairman of its Research Advisory Committee during the period 1938–45.

Without further attempt to list his many affiliations or recount his accomplishments, it is clear that the Fellowship Committee had no difficulty whatsoever

in selecting William Dunford Appel as a Founding Fellow of T.R.I.

Frederic Bonnet

Our second Founding Fellow, alphabetically speaking, is Dr. Frederic Bonnet, Jr. Born in St. Louis, Missouri, he received his B.S. degree in chemistry, *cum laude*, from Washington University in St. Louis in 1899, then pursuing graduate studies at Harvard, where he was awarded the Ph.D. in 1903. While Appel began as a zoologist, Bonnet apparently initially intended to pursue a teaching career (one can never tell who will turn into a textile technologist). After a year as instructor in chemistry in the Medical Department of the State University of Iowa, he served successively as instructor, assistant professor, and professor of chemistry at Worcester Polytechnic Institute.

In May, 1918, he entered into a brief period in the government research field as Chief Chemist of the U. S. Ammonium Nitrate Plant of Perrypoint, Maryland, but in December, 1918, the industrial research bug finally bit him and he has been infected ever since. At that time, he joined the Atlas Powder Company, serving as director of the Forcite Explosives Laboratory and later of the Wilmington Experimental Laboratory. During this period with Atlas, Dr. Bonnet made several trips to Germany to investigate the cuprammonium process for making "artificial silk" and in 1920 he spent 3 months participating technically in its production in a German plant. In 1925 he joined the American Viscose Corporation, where he developed a sales service department, which later became the Textile Research and Standards Department and finally the Standards Department when the Textile Research Department was established in 1939. He retired as Director of the Standards Department in 1946 to become technical advisor to the president of American Viscose.

Those who have visited the Avisco Standards Department at Marcus Hook will agree that it stands as a monument both to a career of technical achievement and to the "rayon ambassador to the American public." He played a salient role in demonstrating to converters, dyers, and finishers that rayon could be made into a reasonably stable fabric if overstretching is avoided. While a considerable number of his many published papers might be classed as "informative" rather than original technical contributions, all of them reveal a deep but practical knowledge of textiles, which, applied to consumer problems of the rayon industry, has been of enormous importance. His present analysis of the fabric flammability problem and its clear presentation before state legislatures and congressional committees undoubtedly will rank as a major contribution both to the rayon industry and to public safety.

Dr. Bonnet has been active in many professional organizations. He has been a Fellow of the American Association for the Advancement of Science since 1906, a member of the American Chemical Society, the American Association of Textile Chemists and Colorists, The Fiber Society, and has been active in A.S.T.M. He is one of the four honorary members of the American Association of Textile Technologists and served for several terms as a Director of T.R.I. and as a member of its Research Advisory Committee. As one who has made and is continuing to make great and valuable contributions to textile technology, it is certainly fitting that Frederic Bonnet, Jr., be designated as a Founding Fellow of T.R.I.

Edward R. Schwarz

We now come to the third member of our triumvirate of Founding Fellows, Prof. Edward Robinson Schwarz. The few remaining moments permit only a cursory glance at his long and varied list of achievements and honors. Born in Lawrence, Massachusetts, it was natural that he should attend M.I.T. and study textiles. He interrupted his studies for a year in order to work in a mill and gain an insight into practical textile problems. Returning to M.I.T., he was appointed a research assistant in the Textile Section and received the Bachelor of Science degree in 1923. It is apparent that he liked M.I.T. quite well, for he stayed on with successive appointments as research assistant, instructor, assistant and associate professor, and finally professor of textile technology and Head of the Textile Division. But there had been no Textile Division of M.I.T. when Edward Schwarz completed his studies in the Textile Section, nor were there offered graduate courses in textile research. While Schwarz liked M.I.T. well enough to stay, he was not satisfied with that institution's facilities for textile education and research; hence, he set out early to build what is now one of the finest institutions of this type in the world. But, as he built, the building became easier with each year, for he developed rapidly into one of the world's outstanding textile scientists and educators. Slater Laboratory stands, in most minds, as a monument to

Ed Schwarz' vision, perseverance, and brilliance. The long list of his students and their accomplishments represents his remarkable and enviable record to an extent equaled only by the value and scope of the work reported in his many publications.

Schwarz must have been a very busy man during this period of building the Textile Division, developing an outstanding educational program and producing valuable research in great volume. But somehow he had time for other activities where his contributions have been truly great. For example, it should be remembered that he served actively on the Advisory Committee for Scientific Research of The Textile Foundation and selected and supervised the research of eighteen Textile Foundation Fellows. Their work, published mainly in the predecessor of TEXTILE RESEARCH JOURNAL, *Textile Research*, constitutes further evidence of his energy and scientific ability. Furthermore, he was largely responsible for the initial phases of the cooperative program between The Textile Foundation and T.R.I. If this cooperative effort now seems to be bearing fruit, tribute must therefore be paid to Ed Schwarz. Incidentally, he served as a Director of T.R.I. for 10 years and was Vice-President for 5 years, 1935–40. He has been an important factor in developing the Institute's publication program and still serves as an Associate Editor of TEXTILE RESEARCH JOURNAL.

Professor Schwarz has been a Fellow of The Textile Institute of Great Britain since 1934, is a Fellow of A.A.A.S., and an honorary member of the American Thread Institute. He holds membership in many other scientific societies and was given the signal honor of the Olney Medal by A.A.T.C.C. in 1947.

It would be hopeless to attempt a brief account of Ed Schwarz' many researches, which embrace the physics and chemistry of all types of fibers as well as yarns and fabrics made from them. But it would be unfortunate to omit mention of his valuable contributions during World War II wherein he directed research in Slater Laboratory for the Army Air Force and the Office of The Quartermaster General. He was a member of the Scientific Advisory Board to the Research and Development Branch, Military Planning Division, O.Q.M.G., member of the Advisory Board to The Aero-Medical Committee, and a consultant to the Textile Section of W.P.B.

To Edward Robinson Schwarz, then, rightly belongs the honor of Founding Fellow of T.R.I.

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